Periphyton growth in Northland rivers

Current status, and development of relationships for nutrient limit-setting

Prepared for Northland Regional Council (Envirolink Fund)

June 2019

Prepared by:
Cathy Kilroy
Rick Stoffels

For any information regarding this report please contact:

Cathy Kilroy
Freshwater Ecologist

+64-3-343 7883
cathy.kilroy@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
PO Box 8602
Riccarton
Christchurch 8011

Phone +64 3 348 8987

NIWA CLIENT REPORT No:	2019064CH
Report date:	June 2019
NIWA Project:	ELF19501

Quality Assurance Statement		
	Reviewed by:	Clive Howard-Williams
	Formatting checked by:	Rachel Wright
	Approved for release by:	Helen Rouse

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The National Policy Statement for Freshwater Management 2014 (NPS-FM) requires regional councils to monitor a range of freshwater attributes defined in the National Objectives Framework as part of a process of understanding, managing and improving the state of New Zealand's fresh waters. The state of ecosystem health in rivers is currently represented by the attribute for periphyton biomass (as chlorophyll *a* in mg/m^2 of river bed).

In 2017, the Government amended the NPS-FM to require regional councils to "at least set appropriate instream concentrations and exceedance criteria for dissolved inorganic nitrogen (DIN) and dissolved reactive phosphorus (DRP)" for the purposes of managing periphyton biomass.

The NPS-FM periphyton metric specifies monthly time series of periphyton observations (as chlorophyll *a*) for at least three years. The metric used for grading a site is the 92nd percentile of chlorophyll *a* (hereafter referred to as "Chla_92"), which is equivalent to at least three exceedances of the thresholds separating bands A and B (50 mg/m^2), B and C (120 mg/m^2) and C and D (200 mg/m^2) recorded during three years of monthly monitoring.

Collection of other environmental data at the same monitoring sites over that period also allows progress towards meeting the requirements of the 2017 amendment to the periphyton attribute of the NPS-FM.

To fulfil its obligations in relation to the NPS-FM periphyton attribute, Northland Regional Council (NRC) expanded its existing State-of-the-Environment periphyton monitoring programme to monthly monitoring at 39 sites, starting in January 2015.

In mid-2018, NRC obtained Envirolink funding to enable NIWA to carry out an analysis of data collected in the first three years of the monitoring programme. NRC requested analysis to address the four sets of questions, three of which are addressed in this report and shown below in italics.

> *Q1: "Is there a problem with periphyton in Northland (as determined from exceedances of MfE guidelines and breaches of the "national bottom line" (D band) of the periphyton attribute in the National Policy Statement for Freshwater Management (NPS-FM))? The analysis will include identification of problem sites for periphyton growth measured as both chlorophyll a biomass and percentage cover and including cyanobacteria."*

The Ministry for the Environment (MfE) 2000 Periphyton Guideline proposed limits for periphyton in rivers for the protection of a range of instream values. Percentages of sites not complying with the MfE 2000 periphyton guidelines over the period of monthly monitoring (January 2015 to May 2018) ranged from 90% (35 of 39 sites) for mean chlorophyll *a* to protect benthic biodiversity (< 15 mg/m^2) to 33% (13 of 39 sites) at which the highest threshold (maximum chlorophyll *a* < 200 mg/m^2) set for the protection of trout habitat and angling values was exceeded at least once in the monitoring period.

Thirty-two sites (82%) were graded into bands A or B of the NPS-FM periphyton attribute (indicating natural or near-natural nutrients and habitat), and two sites (5%) into band D (indicating nutrient enrichment and non-natural habitat, below the national "bottom line"). The band D sites were Hakaru at Topuni and Waiharakeke at Stringers Road. Five sites were graded as band C (Awanui at FNDC, Opouteke at Suspension Bridge, Punakitere at Taheke, Waipapa at Landing, Watercress at SH1).

Over the whole monitoring period, one-third of all sites exceeded the Alert level of the 2009 Cyanobacteria Guideline (>20% cover of the stream bed), and 10% of sites exceeded the Action level (>50% cover of the stream bed) at least once. All exceedances of the Action guideline level were in 2015 or 2016. The sites with highest cover by cyanobacteria were not necessarily the sites that exceeded the MfE guidelines or the sites that were graded into bands C or D of the NPS-FM.

In summary, the periphyton data from 39 Northland sites indicates that a small proportion (5%) of sites have a periphyton "problem" (i.e., excessive periphyton) and a further 13% could potentially be problematic, when assessed against the NPS-FM. The rate of problem sites (graded as NPS-FM band D) was similar to that in recent analysis of a national dataset that included the Northland sites.

> *Q2: "What are the major drivers of periphyton growth in Northland? In particular, what are the roles of dissolved inorganic nitrogen (DIN), dissolved reactive phosphorus (DRP) and ammoniacal-N (NH4-N) in driving periphyton and what are appropriate instream nutrient criteria for Northlands hard-bottomed rivers?"*

Relationships between periphyton Chla_92 and environmental variables were explored using regression techniques. Environmental variables that contributed to strong predictive relationships were: mean water temperature, DRP, DIN, flow metrics and substrate (percentage of the bed covered by coarse substrate), with water temperature the strongest predictor. DRP was generally a stronger predictor than DIN, although relationships with either DRP or DIN as predictors were identified.

NH_4-N concentration (NH4N) and NH_4-N as a percentage of DIN (pcNH4) were, respectively, positively and negatively strongly correlated with DIN (or NO_3-N) across all sites. All these predictors were also correlated with Chl-92 in some subsets of sites and could be interchangeably used in models with similar explanatory skill. Similarly, NH4N or pcNH4 were also correlated with DRP in some subsets and the variables were interchangeable in strong models. Because the variables were intercorrelated, it was not possible in this analysis to isolate any effect of NH_4-N on Chla-92 from the effect of DIN, NO_3-N or DRP.

We suggest that further analysis of the monthly time-series of DRP, DIN and NH_4-N (rather than three-year means) may assist in understanding site-specific responses to different nutrient sources.

When considering all 39 sites in combination, we were unable to confidently identify any relationship between Chla_92 and measured environmental variables. However, Chla_92 was predictable within subsets of sites at which periphyton was sensitive to flow (identified using within-site analyses), with mean temperature, DRP or DIN, flow variables and substrate composition as predictors.

The nature of the relationships means that nutrient criteria may need to be site- or river-specific, because the predictions take account of other site conditions (i.e., flow variability, water temperature) as well as nutrients.

Catchment geology (represented by the REC geology class) appeared to influence periphyton – environment relationships. Chla_92 was predictable across sites with catchments dominated by hard sedimentary geology (HS geology class in the REC), with mean temperature and DIN as predictors.

Preliminary nutrient criteria (both DRP and DIN) applicable to Chla_92 of 50, 120 and 200 mg/m^3 (the thresholds separating the NPS-FM periphyton bands) were derived using five relationships. Criteria were read off look-up plots with each of the three Chla_92 values as the predicted value (the estimate), and as the upper limit of the 95% confidence interval (i.e., a higher value than the estimate associated with the same values of predictor variables). The latter provides more conservative (i.e., restrictive) nutrient criteria, but increases confidence that the Chla_92 threshold will not be exceeded.

Look-up diagrams are provided for all five relationships for a range of scenarios (where appropriate). Calculations were performed in spreadsheets, which can be provided to NRC if required.

> *Q3: "Is Northland's current periphyton monitoring programme fit for purpose, in relation to (a) setting numeric freshwater periphyton objectives for Northland's rivers, and (b) monitoring progress towards the achievement of the freshwater objectives in the context of the NPS-FM?"*

Related to question (b) (the primary purpose of the monitoring programme) we concluded that the size of the programme (number of sites) is good compared to the size of the region. Site representation appeared to be good, although a detailed assessment of representativeness was beyond the scope of this project. Sample collection methods are adequate because they follow standard procedures. Sample analysis methods (for chlorophyll *a*) are consistent with those used by at least three other regions.

Related to question (a), we reviewed suitability of the dataset for model development by referring to three steps towards development of nutrient limits suggested in MfE (2018): (1) select suitable periphyton monitoring sites; (2) monitor periphyton; (3) collect data on controlling factors.

For step (1) we concluded that NRC's periphyton dataset covers a reasonably good range of sites in terms of flow variability and nutrient enrichment and is therefore already suitable for preliminary development of periphyton – environment relationships (as presented in this report). However, the number of sites lacking flow data constrained model development. For step (2), we considered that this step was addressed by question (b) above. For step (3) the NRC dataset already includes data on most of the important potential controllers of periphyton.

The following recommendations are aimed at improving the dataset, to enable development of more reliable relationships for deriving nutrient criteria

- Derive modelled flow records to enable flow-based predictor variables to be calculated for all sites. A first step would be to evaluate existing national predictions against existing flow records in Northland.
- In view of the importance of water temperature as a predictor of Chla_92, consider supplementing the existing monthly spot temperature measurements with continuous water temperature logger data.
- A continuous variable to represent shade would be useful in view of the importance of light at the streambed as a predictor of periphyton in previous studies.

1 Introduction

The National Policy Statement for Freshwater Management 2014 (NPS-FM) requires regional councils to monitor a range of freshwater attributes defined in the National Objective Framework, as part of a process of understanding, managing and improving the state of New Zealand's fresh waters. The state of ecosystem health in rivers is currently represented by the attribute for periphyton biomass (i.e., attached algae growing on the beds of rivers). Some periphyton is a natural feature of rivers and is an essential component of the riverine food web. However, over-abundant periphyton degrades rivers from ecological, recreational and cultural perspectives.

The abundance of periphyton is primarily controlled by factors (such as nutrient supply and river flow regime) that vary naturally but can also be related to human activities (Snelder et al. 2013). Periphyton abundance (represented by biomass measured as chlorophyll *a* per unit area of river bed) thus integrates the effects of nutrient availability, flows and other environmental variables such as temperature and light on the river environment.

Nutrient attributes in the NPS-FM currently target protection of ecosystems from the toxic effects of high concentrations of nitrate-N and ammoniacal-N. In 2017, the Government amended the NPS-FM to require regional councils to "at least set appropriate instream concentrations and exceedance criteria for dissolved inorganic nitrogen (DIN) and dissolved reactive phosphorus (DRP)" for the purposes of managing periphyton biomass (NZ Government 2017). The amendment was added as a "note" to the periphyton attribute. The note includes a direction to also take account of downstream receiving environments. Guidance on how councils might set about achieving the requirements of the note was provided by the Ministry for the Environment (MfE) in 2018 (MfE 2018).

The NPS-FM periphyton metric requires monthly time series of periphyton observations (as chlorophyll *a*) for at least three years. Collection of other environmental data at the same monitoring sites over that period also allows progress towards meeting the requirements of the periphyton note, following some of the suggestions in the MfE guidance document (MfE 2018).

To fulfil its obligations in relation to the NPS-FM periphyton attribute, Northland Regional Council (NRC) expanded its existing State-of-the-Environment periphyton monitoring programme, starting in January 2015. NRC currently monitors 39 sites in the Northland region monthly for periphyton and range of other variables. In mid-2018, NRC obtained Envirolink funding to enable NIWA to carry out an analysis of data collected in the first three years of the monitoring programme. NRC requested analysis to address the following questions.

1. Is there a problem with periphyton in Northland (as determined from exceedances of MfE guidelines and breaches of the "national bottom line" (D band) of the periphyton attribute in the National Policy Statement for Freshwater Management (NPS-FM))? The analysis will include identification of problem sites for periphyton growth measured as both chlorophyll a biomass and percentage cover and including cyanobacteria.

2. What are the major drivers of periphyton growth in Northland? In particular, what are the roles of dissolved inorganic nitrogen (DIN), dissolved reactive phosphorus (DRP) and ammoniacal-N (NH_4-N) in driving periphyton and what are appropriate instream nutrient criteria for Northland's hard-bottomed rivers?

3. Is there any correlation between chlorophyll *a* and periphyton cover data? Some sites persistently have a high percentage of mat/filamentous cover but chlorophyll *a* seldom if ever exceeds 200 mg/m^2 (i.e., the national bottom line for periphyton). Can these sites be identified by any other characteristics (e.g., geology)?

4. Is Northland's current periphyton monitoring programme fit for purpose, in relation to (a) setting numeric freshwater periphyton objectives for Northland's rivers, and (b) monitoring progress towards the achievement of the freshwater objectives in the context of the NPS-FM.

The third question above (relationships between chlorophyll *a* and cover) was separated off to be addressed in a separate project. It is mentioned here because the four questions are closely related. This report addresses questions 1, 2 and 4 and comprises the following sections.

Section 2 introduces the Northland periphyton dataset including a description of steps taken to prepare the dataset for analysis.

In **Section 3** we address question 1 above. Periphyton data were compared with guidelines and assessments made of the state of individual sites and of the region.

Section 4 addresses part of question 2 above, focusing on the effect of rivers flow at individual sites on periphyton (as chlorophyll *a*).

The response to Question 2 continues in **Section 5**, in which we explore relationships between chlorophyll *a* (summarised over time as the 92nd percentile) and multiple variables including flows, nutrients and water temperature. The outcomes of the analysis were cross-validated models that showed some potential for use in developing nutrient criteria (as required by the NPS-FM periphyton note) for Northland.

In **Section 6**, promising relationships are used to develop and suggest preliminary nutrient targets applicable to certain river types in Northland.

In **Section 7** the review of the monitoring programme requested in question 4 above is provided.

A brief synthesis and summary of the main outcomes of the study is presented in **Section 8**, along with a summary of recommendations.

2 The Northland periphyton dataset

2.1 Sampling sites

The locations of 39 sites currently included in NRC's monthly periphyton monitoring programme are shown in Figure 2-1 and listed in Table 2-1. For further details of monitoring sites, including summary water quality data, refer to Appendix A.

2.2 Periphyton data

Northland Regional Council (NRC) provided periphyton and water quality data from 39 state of the environment monitoring sites. The record at eight sites began in 2008, with annual periphyton surveys in late summer (March), collecting biomass (chlorophyll *a*) data only. Between 2008 and 2011, annual summer data were available from up to 14 sites. No data from 2012 were provided. In 2013, data collection increased to quarterly (February, May, August and November) at 21 sites in 2013. In 2014, periphyton samples and data were collected monthly over summer at 22 sites (January, February, March, April and November), with a further 10 sites added sampled in November only. Monthly data collection commenced in January 2015 at 36 sites. Three sites were added to the programme in July 2016. Monthly periphyton data provided spanned January 2015 to May 2018.

Periphyton data in both the quarterly and monthly datasets (i.e., from 2013 onwards) comprised chlorophyll *a* and a visual estimate of periphyton cover on the stream bed. Visual estimates were assessments of the percentage of periphyton cover on the stream bed in two categories: filamentous algae (% filaments) and periphyton mats (%mats). In addition, the percentage of the bed covered by potentially toxic cyanobacterial mats (i.e., *Phormidium*, now known as *Microcoleus*) was also recorded (%cyano). Cyanobacterial mats were a subset of periphyton mats (i.e., %mats included %cyano). When cover of the stream bed was less than 100% we assumed that the balance of cover was made up of either thin algal films or bare rock (no visible algae).

In the present analysis, we focused mainly on the monthly dataset that started in January 2015. Data from 2013 and 2014 were assessed in the analysis of river state. Periphyton sample and data collection from 2013 onwards was carried out using the same methods, following methodology adapted from Biggs and Kilroy (2000) and Kilroy et al. (2008).

2.3 Nutrient and environmental data

The NRC dataset included monthly measurements of a range of environmental variables that are known, from previous research, to influence periphyton growth. These included nutrient concentrations (dissolved inorganic nitrogen, DIN; dissolved reactive phosphorus, DRP; and total N and P, TN, TP), water temperature (spot temperatures in °C), electrical conductivity (EC), turbidity, and water clarity. An estimate of the composition of the substrate on the stream bed was also provided for each site. Substrate composition was assessed as percentage cover by bed particles in the following categories: bedrock (continuous), boulder (> 256 mm across), large cobbles (128 – 256 mm across), small cobbles (64 – 128 mm), gravel (32 – 63 mm), fine gravel (0.5 – 32 mm), sand (<0.5 mm, gritty).

River flow data covering the period of periphyton monitoring were available for 21 of the 39 sites. NRC provided the complete records and we extracted from each the time series of daily mean and maximum flows. We used flow data from 2008 onwards (i.e., 10 years of data) to calculate the medium-term median flow at each site.

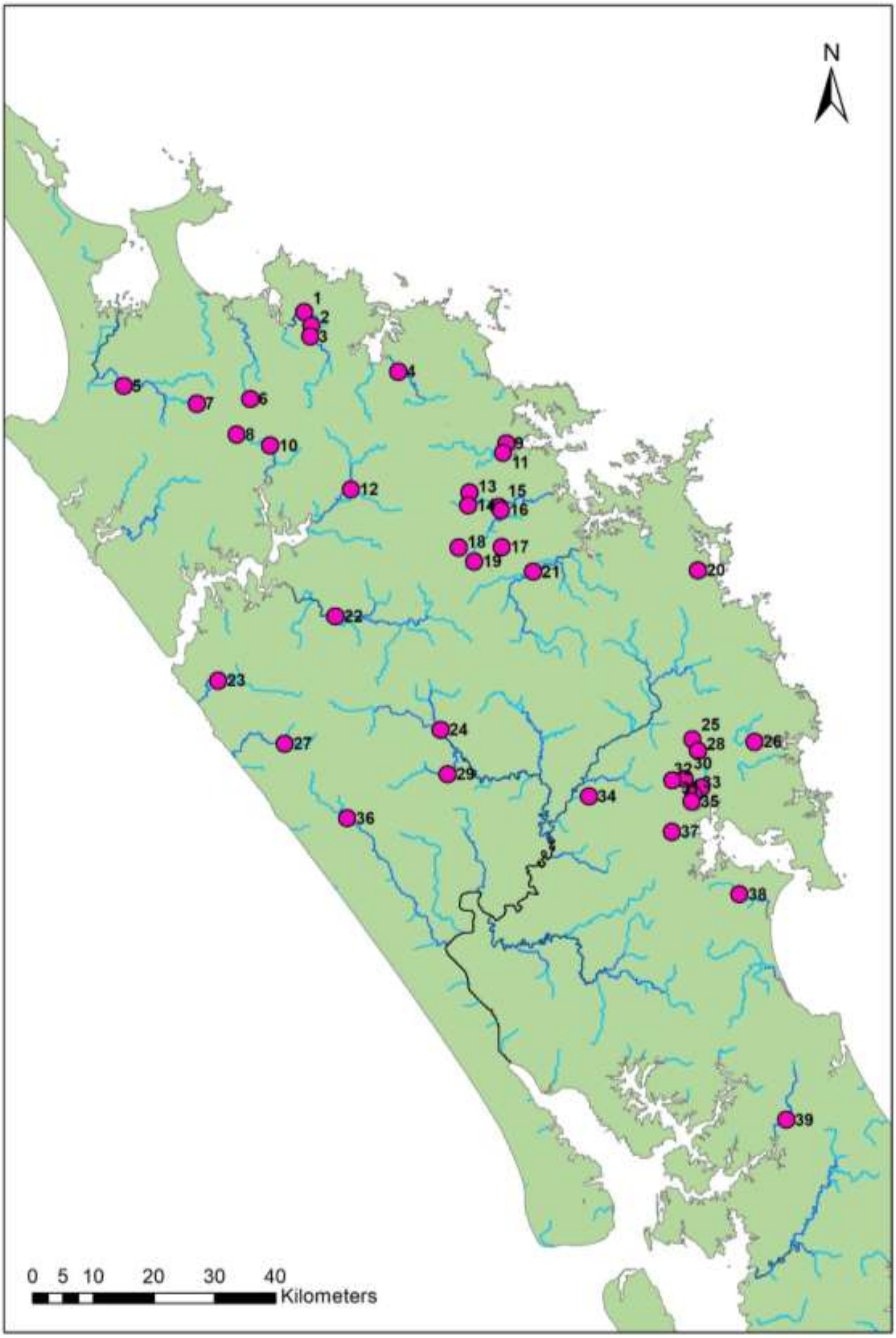

Figure 2-1: Locations of the 39 periphyton monitoring sites in the Northland region. Sites are numbered 1 to 39, ordered from North to South. Refer to Table 2.1 for site details. Note that in the rest of the report, sites are listed alphabetically in tables.

Table 2-1: List of sites included in the Northland periphyton monitoring programme. Sites are numbered from north to south, corresponding to the map in Figure 2-1. Linked hydrological recording are shown. *Flow data provided for these two sites was not current and could not be used in the analysis. Monthly data collection started in January 2015 except for those marked ** (start dates March - July 2016).

N	Site name	E	N	Linked hydrological recording site	
1	Oruaiti at Windust Road	1654906	6125632		
2	Stony Creek at Sawyer Road	1656071	6123396		
3	Oruaiti at Sawyer Road	1655830	6121640		
4	Kaeo at Dip Road	1670326	6115833	2624*	Kaeo at Fire Station
5	Awanui at FNDC	1625095	6113439	1316	Awanui at School Cut
6	Peria at Honeymoon Valley Road	1645966	6111291		
7	Victoria at Victoria Valley Road	1637132	6110554	1351	Victoria at Victoria Valley Road
8	Tapapa at SH1 **	1643752	6105453		
9	Waipapa at Landing	1688150	6103986		
10	Mangamuka at Iwitaua Road	1649247	6103622		
11	Kerikeri at Stone Store	1687631	6102447	3506	Maungaparerua at Tyrees Ford
12	Waipapa at Forest Ranger	1662582	6096421	47804	Waipapa at Forest Ranger
13	Waipapa at Waimate North Road	1682092	6095939		
14	Waitangi at Waimate North Road	1681894	6093741	3725	Waitangi at Waimate North Road
15	Waitangi at SH10	1686946	6093563	43602	Waitangi at SH10
16	Waiaruhe at Puketona	1687317	6093001	3707*	Waiaruhe at Puketona
17	Watercress at SH1	1687416	6086899		
18	Pekepeka at Ohaeawai	1680346	6086802		
19	Waiaruhe d/s Mangamutu Confl.	1682873	6084561		
20	Punaruku at Russell Road **	1719724	6083074		
21	Waiharakeke at Stringers Road	1692604	6082806	3819	Waiharakaka at Willowbank
22	Punakitere at Taheke	1660001	6075453	47595	Punakitere at Taheke
23	Waimamaku at SH12	1640666	6064914		
24	Mangakahia at Twin Bridges	1677333	6056762	46618	Mangakahia at Gorge
25	Mangahahuru at Main Road	1718886	6055192	46674	Mangahahuru at County Weir
26	Ngunguru at Coalhill Lane	1729072	6054775	4901	Ngunguru at Dugmores Rock
27	Waipoua at SH12	1651633	6054443	46902	Waipoua at SH12
28	Mangakino at Mangakino Lane	1719727	6053270		
29	Opouteke at Suspension Bridge	1678503	6049460	1046651	Opuoteke at Suspension Bridge
30	Waiarohia at Whau Valley	1717568	6048671		
31	Pukenui at Kanehiana Drive **	1715556	6048444		
32	Hatea at Mair Park	1720284	6047290	5538	Hatea at Whareora Road
33	Waiarohia at Second Avenue	1719047	6046013	5527	Waiarohia at Lovers Lane
34	Waipao at Draffin Road	1701772	6045796	46641	Waipao at Draffin Road
35	Raumanga at Bernard Street	1718760	6044937	5528	Raumanga at Bernard Street
36	Kaihu at Gorge	1661946	6042161	46611	Kaihu at Gorge
37	Otaika at Otaika Valley Road	1715476	6039940	5659	Otaika at Kay
38	Ruakaka at Flyger Road	1726626	6029623	5901	Ruakaka at Flygers Road
39	Hakaru at Topuni	1734330	5992416	46020	Hakaru at Topuni Creek Farm

2.4 Data preparation

Checks were carried out on the dataset prior to starting any analysis. Nutrient data were converted from mg/L to mg/m^3, to avoid multiple decimal places at low concentrations. Electrical conductivity (EC) data were converted from mS/m to µS/cm, for consistency with data from other regions. We noted that two sites (Hatea at Mair Park and Kerikeri at Stone Store) had very high EC values from time to time. We confirmed with NRC that the outlying values were caused by tidal influence at the sites. It was not possible to assign a typical mean EC at these sites[1] and the sites were omitted from analyses including EC as a predictor.

The following datasets were prepared.

Dataset A included all individual chlorophyll *a* observations at each site since 2013, along with the available water quality variables from samples collected or measurements made contemporaneously. There were 1637 chlorophyll *a* observations in total. Water quality observations were made on the same day in 23% of cases, within 1 day in 57% of cases, and within 3 days in 80% of cases. Water quality and periphyton data were collected more than 7 days apart in <1% of cases. All observations in Dataset A at site with a linked flow record were also linked to hydrological data, and the dataset was used to derive empirical estimates of the flow magnitude required to remove periphyton at each site (see Section 4). The water quality data were not used as single observations but were summarised for dataset B.

Dataset B consisted of site-averaged data derived from the monthly time series of periphyton (January 2015 to May 2018). We first calculated metrics from environmental and flow data to obtain a single line of data representing average data over the entire period. For details of variables and metrics, refer to Section 5.

[1] In the Hatea at Mair Park, conductivity ranged from 110 to 32960 µS/cm (mean 7124). One-third of all readings exceeded 12000 µS/cm and the remaining two-thirds were less than 2100 µS/cm. In the Kerikeri at Stone Store, conductivity ranged from 54 to 3705 µS/cm (mean 621). One-third of all readings exceeded 265 µS/cm and the remaining two-thirds were less than 95 µS/cm.

3 Assessment of periphyton in Northland relative to the NPS-FM and other guidelines

In this section we provide an assessment of the state of periphyton in Northland rivers in relation to national guidelines. NRC asked:

> *"Is there a problem with periphyton in Northland (as determined from exceedances of MfE guidelines and breaches of the "national bottom line" (D band) of the periphyton attribute in the National Policy Statement for Freshwater Management (NPS-FM))? The analysis will include identification of problem sites for periphyton growth measured as both chlorophyll a biomass and percentage cover and including cyanobacteria."*

We mainly used the monthly time series data at the 39 SOE sites, starting in January 2015 to make the assessments. For completeness, we also report exceedances of thresholds in the MfE 2000 guidelines (Biggs 2000) in the data collected in 2013 and 2014.

3.1 Periphyton standards

3.1.1 MfE 2000 guidelines

Guidelines for periphyton, measured as both coverage of the stream bed and as biomass (chlorophyll *a* or ash-free dry mass (AFDM)) were set out by Biggs (2000). The guidelines applied to different instream values and were "effects-based". In other words, the biomass and cover thresholds were shown to be linked to the values, which were aesthetics / recreation, trout habitat / angling and benthic biodiversity (Table 3-1). We assessed all the Northland sites against each guideline, except those that were specified in AFDM (for which there was no data).

3.1.2 NPS-FM

Currently, the key periphyton standards for assessing the ecological state of a site are those described by the four bands of the periphyton attribute of the NPS-FM. The periphyton attribute defines four bands (A to D), each of which is associated with a narrative on river state (New Zealand Government 2017) (Table 3-1). The periphyton attribute requires that periphyton biomass is measured as chlorophyll *a* and allows for two classes: default and productive.[2] The metric for assessing band membership in the default class is more than three exceedances of the threshold separating the bands over a 36-month period of monthly monitoring (i.e., one exceedance per year, on average, of the thresholds). The productive class is allowed one additional exceedance per year, or more than six exceedances over a 36-month period of monthly monitoring.

None of the Northland sites fell into the "productive class". Nine of the 39 sites are classified as having dominant geology in the productive class (SS), but all sites are in the climate class WW (warm wet).

The chlorophyll *a* thresholds separating the bands in the periphyton attribute are nominally the same as those set by Biggs (2000) (Table 3-1), although the metric used is different.

[2] Classes are defined according to types in the River Environment Classification (REC). The productive class includes sites at which periphyton is expected to be naturally high because of naturally occurring high background concentrations of nutrients. The productive class is defined by the combination of REC "Dry" Climate categories (i.e. Warm-Dry (WD) and Cool-Dry (CD)) and REC Geology categories that have naturally high levels of nutrient enrichment due to their catchment geology (i.e. Soft-Sedimentary (SS), Volcanic Acidic (VA) and Volcanic Basic (VB)). Therefore, the productive class is defined by the following REC defined types: WD/SS, WD/VB, WD/VA, CD/SS, CD/VB, CD/VA. The default class includes all REC types not in the productive class.

3.1.3 Cyanobacteria guideline

The New Zealand Guideline for Cyanobacteria (Wood et al. 2009) sets thresholds for percentage cover by cyanobacteria for the protection of human and animal health in rivers. The predominant species of cyanobacteria seen in New Zealand rivers is the potentially toxic *Microcoleus autumnale* (formerly *Phormidium autumnale*). We assumed that percentage cover by cyanobacteria in the dataset referred mainly to this species. The guidelines specify two levels:

> **Alert:** 20−50 per cent coverage of potentially toxic cyanobacteria mats attached to substrate. Attaining alert level at recreational sites is a trigger for more intensive monitoring of both cover and levels of toxins.
>
> **Action:** >50 per cent coverage of the substrate by potentially toxic cyanobacteria mats, or <50 per cent coverage, but accumulation of detached mats along the river margins. Attaining action level at recreational river sites requires a response from regional authorities such as media alerts and erection of signage. Refer to Wood et al. (2009) for details.

Table 3-1: Summary of periphyton and cyanobacteria standards, set to protect a range of instream values. Shaded cells show ADFM, which was not included in the present assessment.

Guideline for protection of:	Periphyton metric	Threshold	Units
MfE guidelines: New Zealand Periphyton Guideline (Biggs 2000)			
Aesthetics / recreation values	Maximum % cover, mats > 3mm thick	60	%
	Max. cover, filaments < 2 cm long	30	%
	Max. AFDM	35	g/m²
Benthic biodiversity	Maximum chlorophyll *a*	120	mg/m²
	Mean monthly chlorophyll *a (over 12 months)*	15	mg/m²
Trout habitat/angling	Maximum chlorophyll *a*	50	mg/m²
	Max. AFDM	35	g/m²
	Maximum chlorophyll *a* (mats)	200	mg/m²
	Maximum chlorophyll *a* (filaments)	120	mg/m²
Periphyton attribute, NPS-FM (NZ Government 2017)			
Ecosystem health of rivers			
Band A, negligible impact	> 8% exceedance (1 of 12), chlorophyll *a* Based on monthly samples, with min. data series of 3 years (i.e., the 92nd percentile of chlorophyll *a*, subsequently referred to as Chla_92)	<50	mg/m²
Band B, low impact		50–120	mg/m²
Band C, moderate impact		120–200	mg/m²
Band D, below "bottom line"		>200	mg/m²
New Zealand Guideline for Cyanobacteria (Wood et al. 2009)			
Human/animal health: alert	Max. cover, *Microcoleus*	20	%
Human/animal health: action	Max. cover, *Microcoleus*	50	%

3.2 Methods

3.2.1 Treatment of missing periphyton data for assessments requiring data over time

The wording in the periphyton attribute of the NPS-FM related to the period over which the grading is made is: "*Based on a monthly monitoring regime. The minimum record length for grading a site based on periphyton (chl-a) is 3 years.*" This is unambiguous and implies that the minimum data used for an assessment against the periphyton attribute must be <u>36 samples collected over three years (i.e., in every consecutive month)</u>. The wording also implies that periods of longer than three years can be used to assess state. The interpretation of the wording is important because the monthly time series at all Northland sites had sampling occasions on which no periphyton data were collected, hereafter termed "missing data". Inclusion or exclusion of the missing data points can affect a grading, depending on how it is calculated.

In practice, a small proportion of missing periphyton data should make little difference to the analysis because the metric of interest is close to the maximum value (a high percentile). However, at sites with high proportions of missing monthly datapoints (e.g., more than 20% missing), using the raw data without compensating for the missing data could lead to upward bias in chlorophyll *a* when assessments against the NPS-FM are made by calculating the 92nd percentile of chlorophyll *a* over the monitoring period. The alternative method of grading a site, by counting numbers of exceedances over periods of 36 months, is not affected by missing data if we make the reasonable assumption that periphyton abundance is always low when samples cannot be collected.

The data were screened for missing data and the percentage missing was calculated for each site from the number of months in the monitoring period for which there was no data (see Appendix A). To compensate for missing data, we completed the time series at each site by inserting into each month with a value calculated as the 5th percentile of the observed values at that site. The 5th percentile of chlorophyll *a* across all measured values was <1 mg/m^2, which represents algae comprising films, or no algae (Kilroy et al. 2013). This resulted in a downward adjustment of mean chlorophyll *a* by 17% on average (median 12%), and of the 92nd percentile of chlorophyll *a* by 11% on average (median 4%).

3.2.2 Assessments

Annual means (for the MfE guideline for protection of benthic biodiversity) were calculated in each calendar years (for simplicity), adjusted for missing data as described above. Numbers of exceedances of the MfE chlorophyll *a* and %cover thresholds (Table 3-1) were extracted at each site and in each calendar year. Similarly, we extracted annual numbers of exceedances of the cyanobacteria guidelines.

All monthly chlorophyll *a* data (2015 onwards) were used to calculate the 92nd percentile at each site (hereafter referred to as Chla_92), for the NPS-FM periphyton attribute, with adjustment for missing data. Numbers of exceedances of the three thresholds separating bands A/B, B/C and C/D were also extracted for the 36 months from January 2015.

Both adjusted and unadjusted results are reported for the assessment that required mean annual chlorophyll *a* (MfE 2000, benthic biodiversity) and the 92nd percentile (NPS-FM), to evaluate the effect of the adjustment.

3.3 Results

3.3.1 MfE 2000 guidelines

Aesthetics / recreation values

There were no exceedances of either of the percentage cover thresholds at three sites over the entire period of monitoring (Pukenui at Kanehiana Drive, Tapapa at SH1, Waipoua at SH12), although monitoring at Pukenui has been underway only since mid-2016 (Table 3-2).

There was a single exceedance at two sites (Hatea at Mair Park, mats in 2015; Waitangi at SH10, filaments in 2017) (Table 3-2). Highest rates of exceedance of the 30% filaments thresholds were at Hakaru at Topuni, Opouteke at Suspension Bridge, Oruaiti at Sawyer Road and Waipapa at Landing.

Highest rates of exceedance of the 60% mats threshold were at Pekepeka at Ohaeawai and Waipapa at Waimate North Road.

There was a higher rate of exceedances (i.e., lower compliance) in 2015 than in other years, indicating more favourable conditions for accrual of periphyton cover in that period.

Benthic biodiversity

Mean monthly chlorophyll *a* over twelve months (adjusted for missing data) was below the threshold of 15 mg/m^2 in all three calendar years at four sites (Mangaharuru at Main Road, Mangamuka at Iwitaua Road, Waipapa at Forest Ranger, Waipoua at SH12), and exceeded the threshold in all three years at 13 sites (Table 3-3).

The most severe exceedance was in the Hakaru at Topuni, where mean chlorophyll *a* was at least 15 times the threshold in all three years with complete data. Other sites where mean chlorophyll *a* exceeded the threshold at least four-fold were (in order, highest first) Awanui at FNDC, Waiharakeke at Stringers Road, Opouteke at Suspension Bridge, Punakitere at Taheke, and Waipapa at Landing.

There was only one case where unadjusted data returned exceedance of the threshold, while adjusted data did not (Waitangi at Waimate North Road in 2017, Table 3-3).

The threshold for maximum chlorophyll *a* (50 mg/m^2) was exceeded at least once at 31 of 36 sites (79%), 22 of 39 sites (56%) in 2016 and 19 of 39 sites (49%) in 2017 (Table 3-4). Highest rates of exceedance (across all years) were at Hakaru at Topuni (27 exceedances) and Pekapeka at Ohaeawai (16), Opouteke at Suspension Bridge (15), Waipapa at Landing (14).

Trout habitat and angling

Two sites (Hakaru at Topuni, Waiharakeke at Stringers Road) had persistent high chlorophyll *a* that breached the Biggs (2000) thresholds of 120 and 200 mg/m^2 in the three years with complete data. The thresholds for maximum chlorophyll *a* of 120 and 200 mg/m^2 were exceeded at least once at 21 and 11 of 36 sites (58% and 31% respectively) in 2015, 16 and seven of 39 sites (41% and 18% respectively) in 2016, and at eight and three of 39 sites (21% and 8% respectively) in 2017 (Table 3-4). Note that we did not distinguish between chlorophyll *a* from mats and filaments, as specified in the Biggs (2000) guideline, because cover was usually a mixture of mats and filaments and the main source of chlorophyll *a* could not be determined.

Table 3-2: Numbers of exceedances of 30% cover by filaments and 60% cover by mats. Thresholds used to assess compliance with the MfE 2000 guidelines for protection of aesthetics / recreation values. Grey shaded panels indicate data from 2013 and 2014 (for completeness). A dash indicates no data. 2015 to 2018 are calendar years. Blue shaded data indicate that the time series started part way through the year. *note that 2018 data are for five months only. Brown shaded cells show sites with high exceedance rates.

	Exceedances of 30% cover, filaments						Exceedances of 60% cover, mats					
Site	**2013**	**2014**	**2015**	**2016**	**2017**	**2018***	**2013**	**2014**	**2015**	**2016**	**2017**	**2018***
Awanui at FNDC	4	3	3	1	2							
Hakaru at Topuni	3	2	7	7	4	4			4	1	4	
Hatea at Mair Park									1			
Kaeo at Dip Road	-	-	2	1	2		-	-	1			
Kaihu at Gorge	2	1		2								3
Kerikeri at Stone Store			1	1					2			
Mangahahuru at Main Road		1									1	
Mangakahia at Twin Bridges	4	3	3	1	1				2			
Mangakino at Mangakino Lane	-	-					-	-			1	
Mangamuka at Iwitaua Road	1	3	1	1					1			
Ngunguru at Coalhill Lane	-	-		2			-	-	1			
Opouteke at Suspension Bridge	5	4	3	2	1	1			6	1		1
Oruaiti at Sawyer Road	-	-	2	3	5	1	-	-	2			
Oruaiti at Windust Road	-	-	5	1			-	-				
Otaika at Otaika Valley Road		1	2		2							
Pekepeka at Ohaeawai	-	-		4			-	-	3	2	8	4
Peria at Honeymoon Valley Road	-	-	1		1		-	-				
Pukenui at Kanehiana Drive	-	-	-				-	-	-			
Punakitere at Taheke		2	2			-						-
Punaruku at Russell Road	-	-	-				-	-			1	1
Raumanga at Bernard Street	-	-	4	1			-	-	1			
Ruakaka at Flyger Road			1						1	2	2	
Stony Creek at Sawyer Road	-	-	2				-	-				
Tapapa at SH1	-	-	-				-	-				
Victoria at Victoria Valley Road	4	1	1					1	1			
Waiarohia at Second Avenue	2	3	4	3	1					2		2
Waiarohia at Whau Valley	2		1						1	1		
Waiaruhe at Puketona	-	-					-	-	2		1	
Waiaruhe d/s Mangamutu Confl.	-	-		1			-	-	1		1	
Waiharakeke at Stringers Road	2		2	1	1							
Waimamaku at SH12	-	1			1		-			1		
Waipao at Draffin Road		1	1	1	1							
Waipapa at Forest Ranger			1									
Waipapa at Landing	1	1	2	4	2	1			2			
Waipapa at Waimate North Road	-	-	1		1		-	-	6	2	3	
Waipoua at SH12												
Waitangi at SH10	-	-			1		-	-				
Waitangi at Waimate North Road	1											
Watercress at SH1	-	-	6		1		-	-				
Total exceedances, all sites	**31**	**27**	**58**	**37**	**27**	**7**		**1**	**38**	**12**	**22**	**11**
Percentage, all months & sites			**12.4**	**7.9**	**6.2**	**11.7**						

Table 3-3: Mean annual chlorophyll *a* calculated for 2015, 2016 and 2017 at 39 Northland river sites. Data from January to December in each year. Shaded cells indicate sites and year in which 15 mg/m^2 was exceeded. Bold highlighted sites had overall mean Chl a > 60 mg/m^2. Two means are provided for each year. Chl a is the mean value of the available data in the 12-month period. Adj. Chl a is the mean value after the time series was adjusted to compensate for all missing values using the method in Section 3.2.1. - = no data. Blue shading indicates a part year of data.

	2015		2016		2017	
Site	Chl a	Adj Chl a	Chl a	Adj Chl a	Chl a	Adj Chl a
Awanui at FNDC	119	100	97	81	39	18
Hakaru at Topuni	282	261	279	238	387	239
Hatea at Mair Park	29	22	6	6	6	6
Kaeo at Dip Road	17	17	8	8	7	7
Kaihu at Gorge	32	28	64	64	24	24
Kerikeri at Stone Store	38	38	42	42	29	27
Mangaharuru at Main Road	7	7	13	13	8	8
Mangakahia at Twin Bridges	45	41	52	52	12	12
Mangakino at Mangakino Lane	39	39	5	4	4	4
Mangamuka at Iwitaua Road	11	11	3	3	11	8
Ngunguru at Coalhill Lane	37	34	27	27	21	21
Opouteke at Suspension Bridge	90	90	123	95	24	20
Oruaiti at Sawyer Road	68	57	28	28	34	29
Oruaiti at Windust Road	35	32	23	23	5	5
Otaika at Otaika Valley Road	66	61	28	28	14	14
Pekapeka at Ohaeawai	52	52	52	52	28	28
Peria at Honeymoon Valley Road	58	58	32	32	14	14
Pukenui at Kanehiana Drive	-	-	2	2	2	2
Punakitere at Taheke	113	86	53	33	5	5
Punaruku at Russell Road	-	-	4	4	3	3
Raumanga at Bernard Street	53	53	22	19	4	4
Ruakaka at Flyger Road	30	27	16	16	16	16
Stony Creek at Sawyer Road	34	31	8	8	3	3
Tapapa at SH1	-	-	10	10	2	2
Victoria at Victoria Valley Road	17	17	7	7	10	10
Waiarohia at Second Avenue	60	56	34	34	21	21
Waiarohia at Whau Valley	40	40	35	30	9	9
Waiaruhe at Puketona	18	15	20	20	9	8
Waiaruhe d/s Mangamutu Confl.	52	52	13	13	2	2
Waiharakeke at Stringers Road	101	85	118	90	71	38
Waimamaku at SH12	20	18	15	13	24	16
Waipao at Draffin Road	27	23	25	25	20	20
Waipapa at Forest Ranger	14	14	5	5	6	6
Waipapa at Landing	63	63	76	76	49	42
Waipapa at Waimate North Road	16	16	18	18	13	12
Waipoua at SH12	8	8	3	3	2	2
Waitangi at SH10	28	21	3	2	3	2
Waitangi at Waimate North Road	15	15	2	2	18	9
Watercress at SH1	80	80	55	41	31	31

Table 3-4: Numbers of exceedances of chlorophyll *a* thresholds from the 2000 periphyton guideline at each Northland periphyton monitoring site, by year. Grey-shaded panels indicate 2013 and 2014, when periphyton surveys were quarterly. A dash indicates no data. 2015 to 2018 are calendar years. Blue shaded cells indicate that the monthly time series for that site started part way through the year. *note that 2018 data are for five months only.

	Exceedances of 50 mg/m²						Exceedances of 120 mg/m²						Exceedances of 200 mg/m²					
Site	2013	2014	2015	2016	2017	2018*	2013	2014	2015	2016	2017	2018*	2013	2014	2015	2016	2017	2018*
Awanui at FNDC	1	2	3	5	2			1	3	4					1	1		
Hakaru at Topuni	2	1	10	9	6	2	1	1	8	7	4	1	1		3	4	4	1
Hatea at Mair Park	1		2						1									
Kaeo at Dip Road	-	-	1				-	-					-	-				
Kaihu at Gorge	1	1	3	5	2	1				2						1		
Kerikeri at Stone Store			4	3	1	1			1									
Mangahahuru at Main Road																		
Mangakahia at Twin Bridges	1	4	3	5			1	1	1	2			-	-		1		
Mangakino at Mangakino Lane	-	-	3				-	-	1									
Mangamuka at Iwitaua Road		1			1													
Ngunguru at Coalhill Lane	-	-	3	4	1	1	-	-			1		-	-				
Opouteke at Suspension Bridge	1	2	7	5	1	2	1	1	5	2		1			1	1		
Oruaiti at Sawyer Road	-	-	3	1	3		-	-	2				-	-	1			
Oruaiti at Windust Road	-	-	2	2			-	-	1	1			-	-				
Otaika at Otaika Valley Road		2	4	1				2	2	1					1			
Pekepeka at Ohaeawai	-	-	6	4	2	4	-	-	1	1			-	-				
Peria at Honeymoon Valley Road	-	-	4	3	1		-	-	1	1	1		-	-	1			
Pukenui at Kanehiana Drive	-	-	-				-	-	-				-	-	-			
Punakitere at Taheke			5	2					2	1					2	1		
Punaruku at Russell Road	-	-	-				-	-	-				-	-	-			
Raumanga at Bernard Street			3	1					2	1								
Ruakaka at Flyger Road			2	1	1	1			1									
Stony Creek at Sawyer Road	-	-	3				-	-					-	-				
Tapapa at SH1	-	-	-				-	-	-				-	-	-			
Victoria at Victoria Valley Road		1	2		1													
Waiarohia at Second Avenue		3	7	2	1	1		2	1					1				
Waiarohia at Whau Valley			4	3						1								
Waiaruhe at Puketona	-	-	1	2	1	1	-	-		1			-	-				

Site	Exceedances of 50 mg/m²						Exceedances of 120 mg/m²						Exceedances of 200 mg/m²					
	2013	2014	2015	2016	2017	2018*	2013	2014	2015	2016	2017	2018*	2013	2014	2015	2016	2017	2018*
Waiaruhe d/s Mangamutu Confl.	-	-	3	1		1	-	-	1				-	-	1			
Waiharakeke at Stringers Road			5	3	3				4	3	1				2	3	1	
Waimamaku at SH12	-		1		1		-				1		-					
Waipao at Draffin Road		1	2	2	1				1		1							
Waipapa at Forest Ranger																		
Waipapa at Landing			5	5	2	2			1	4	2	1			1			
Waipapa at Waimate North Road	-	-					-	-					-	-				
Waipoua at SH12			1															
Waitangi at SH10	-	-	1				-	-					-	-				
Waitangi at Waimate North Road					1													
Watercress at SH1	-	-	6	4	1		-	-	4	2	1		-	-	1		1	
Total exceedances, all sites	7	18	109	73	33	17	3	8	44	34	12	3	1	1	15	12	6	1
Total sites with exceedances			31	23	20	11			21	16	8	3			11	7	3	1

3.3.2 NPS-FM periphyton attribute

Sixteen sites each were placed in bands A and B, five sites were placed in band C and two sites in Band D (below the bottom line) (Hakaru at Topuni and Waiharakeke at Stringers Road) (Table 3-5). These assessments were consistent with those obtained using numbers of exceedances in the 36-month period from January 2015 to December 2017. Using unadjusted data, one additional site (Punakitere at Taheke) would have been placed in Band D of the periphyton attribute of the NPS-FM. We suggest that methods that assess sites against the NPS-FM periphyton attribute bands from calculations of the 92nd percentile of chlorophyll *a* should not be used unless the data are adjusted to allow for missing values.

3.3.3 Cyanobacteria guideline

Between January 2015 and May 2018, there were 17 exceedances of the Alert level of the cyanobacteria guideline and five exceedances of the Action level (Table 3-6). Thirteen of the 39 monitoring sites were affected and at seven of these there was just one exceedance over the 42-month monitoring period. One site (Ruakaka at Flyger Road) had exceedances in three years. Three sites had exceedances in two years: Kerikeri at Stone Store, Ngunguru at Coalhill Lane, Opouteke at Suspension Bridge.

Most exceedances were in 2015 (10 Alerts and three Actions). Nine sites were affected in 2015, one of which (Waiaruhe d/s Mangamutu Confl.) had three exceedances, including two exceedances of the Action level.

Cyanobacteria was more widespread that than the guideline exceedances indicated, with 32 of the 39 monitoring sites having some cover by cyanobacteria at least once between January 2015 and May 2018. Across all sites, cover by cyanobacteria was recorded in 249 of 1642 visual estimate surveys (~15%). Cover ranged from <0.1% to >70%, the latter in the Kerikeri at Stone Store.

3.3.4 Overall state of Northland rivers relative to periphyton standards

Percentages of sites <u>not complying</u> with the MfE guidelines over the period of monthly monitoring (January 2015 to May 2018) ranged from 90% (35 of 39 sites) for the most stringent standard (mean chlorophyll *a* to protect benthic biodiversity) to 33% for the highest threshold (maximum chlorophyll *a*) (Table 3-7).

Thirty-two sites (82%) were graded into bands A or B of the NPS-FM periphyton attribute, five (13%) into band C and two (5%) into band D (Table 3-7). Note that the number of sites exceeding 200 mg/m^2 in the MfE guidelines was much higher than the number of sites below graded into band D of the NPS-FM because just one exceedance breaches the MfE guideline, whereas the NPS-FM requires at least three exceedances over three years.

Over the whole monitoring period, one-third of all sites exceeded the Alert level of the cyanobacteria guideline, and 10% of sites exceeded the Action level at least once. All exceedances of the guideline Action level were in 2015 and 2016 (Table 3-7). The sites with highest cover by cyanobacteria were not necessarily the sites that exceeded the MfE guidelines or were graded into bands C or D of the NPS-FM.

Table 3-5: Assignment of 39 sites in Northland to bands of the periphyton attribute of the NPS-FM. Gradings (blue, A; green, B; amber, C; red, D) were calculated using two methods. 1. Samples within the ranges specified for each band were counted (see Table 3-1). More than three samples in the range places the site in bands D, C or B. A site is in band A when ≤ 3 samples exceed 50 mg/m^2 in a three-year period. 2. TChla_92 was calculated over the whole time series. The "Adjust." Column shows the result after taking account of missing data (see Section 3.2.1). The result for Punakitere at Takehe illustrates that adjustment is needed to obtain consistent results. ** Provisional grading as less than 3 years of data available.

	N samples in range of Band				N		Chla_92	
Site	A	B	C	D	samples	surveys	Unadj.	Adjust.
Awanui at FNDC	16	3	5	2	26	30	186.2	173.5
Hakaru at Topuni	6	7	8	11	33	34	744.6	717.0
Hatea at Mair Park	35	1	1		37	37	15.6	14.7
Kaeo at Dip Road	38	1			39	40	26.8	26.8
Kaihu at Gorge	27	9	1	1	38	39	66.9	66.9
Kerikeri at Stone Store	30	8	1		39	40	63.5	63.5
Mangahahuru at Main Road	39				39	40	22.6	22.6
Mangakahia at Twin Bridges	29	5	2	1	37	40	102.4	96.9
Mangakino at Mangakino Lane	37	2	1		40	40	38.1	38.1
Mangamuka at Iwitaua Road	36	1			37	38	23.6	22.1
Ngunguru at Coalhill Lane	29	8	1		38	40	77.3	77.4
Opouteke at Suspension Bridge	17	7	6	2	32	35	167.5	153.7
Oruaiti at Sawyer Road	27	5	1	1	34	37	108.0	106.7
Oruaiti at Windust Road	34	2	2		38	38	63.5	61.7
Otaika at Otaika Valley Road	35	2	2	1	40	40	67.3	52.6
Pekapeka at Ohaeawai	25	14	2		41	41	88.6	85.4
Peria at Honeymoon Valley Road	33	5	2	1	41	41	108.6	110.3
Pukenui at Kanehiana Drive **	23				23	23		
Punakitere at Taheke	14	4		3	21	26	203.3	132.8
Punaruku at Russell Road **	22				22	23	8.6	8.9
Raumanga at Bernard Street	35	1	3		39	40	79.8	46.7
Ruakaka at Flyger Road	35	4	1		40	40	63.7	63.1
Stony Creek at Sawyer Road	37	3			40	40	24.3	24.6
Tapapa at SH1 **	21				21	22	5.9	5.1
Victoria at Victoria Valley Road	36	3			39	40	30.6	30.6
Waiarohia at Second Avenue	28	10	1		39	40	112.7	112.7
Waiarohia at Whau Valley	33	6	1		40	40	65.9	65.9
Waiaruhe at Puketona	33	4	1		38	38	54.7	54.4
Waiaruhe d/s Mangamutu Confl.	28	4		1	33	35	82.4	52.1
Waiharakeke at Stringers Road	17	3	2	6	28	30	291.1	250.5
Waimamaku at SH12	32	1	1		34	35	33.8	30.1
Waipao at Draffin Road	33	3	2		38	39	54.2	54.2
Waipapa at Forest Ranger	39				39	38	32.0	31.7
Waipapa at Landing	24	6	7	1	38	39	160.3	160.3
Waipapa at Waimate North Road	39				39	40	34.4	34.4
Waipoua at SH12	40	1			41	41	4.2	4.3
Waitangi at SH10	24	1			25	27	37.2	29.8
Waitangi at Waimate North Road	30	1			31	34	35.6	31.9
Watercress at SH1	24	4	5	2	35	37	155.7	154.3

Table 3-6: Summary of exceedances of the cyanobacteria guidelines. Years are calendar years. Numbers of exceedances are shown. Green cells = acceptable (< 20% cover); amber cells = alert (20 – 50% cover); red cells = action (>50% cover). Blue shading indicates that monitoring started part way through the year. - = no data. *2018 data from January to May only.

Site	2015 Alert	2015 Action	2016 Alert	2016 Action	2017 Alert	2017 Action	2018* Alert	2018* Action
Awanui at FNDC								
Hakaru at Topuni								
Hatea at Mair Park								
Kaeo at Dip Road								
Kaihu at Gorge	1							
Kerikeri at Stone Store		1			1			
Mangahahuru at Main Road								
Mangakahia at Twin Bridges			1					
Mangakino at Mangakino Lane								
Mangamuka at Iwitaua Road								
Ngunguru at Coalhill Lane	1				1			
Opouteke at Suspension Bridge	1		1					
Oruaiti at Sawyer Road	1							
Oruaiti at Windust Road								
Otaika at Otaika Valley Road								
Pekepeka at Ohaeawai								
Peria at Honeymoon Valley Road								
Pukenui at Kanehiana Drive	-	-						
Punakitere at Taheke			1					
Punaruku at Russell Road	-	-						
Raumanga at Bernard Street								
Ruakaka at Flyger Road	2			1			1	
Stony Creek at Sawyer Road								
Tapapa at SH1	-	-						
Victoria at Victoria Valley Road								
Waiarohia at Second Avenue								
Waiarohia at Whau Valley								
Waiaruhe at Puketona								
Waiaruhe d/s Mangamutu Confl.	1	2						
Waiharakeke at Stringers Road	2							
Waimamaku at SH12								
Waipao at Draffin Road								
Waipapa at Forest Ranger								
Waipapa at Landing								
Waipapa at Waimate North Road				1				
Waipoua at SH12								
Waitangi at SH10	1							
Waitangi at Waimate North Road							1	
Watercress at SH1								
Grand Total	10	3	3	2	2		2	

Table 3-7: Summary of compliance with MfE periphyton guidelines, NPS-FM grading, and compliance with cyanobacteria guidelines in Northland. NPS-FM band assessed based on data from 2015-17 only. *Note that three sites in band A were assessed provisionally from less than the required 36 months of data.

Guideline or standard	Metric	Threshold or range	Percentage sites compliant in period 2015 -18	2015	2016	2017	2018*
MfE guidelines: New Zealand Periphyton Guideline (Biggs 2000)							
Aesthetics / recreation	Maximum % cover, mats	60%	38	50	79	77	87
	Max. cover, filaments	30%	23	33	54	59	89
Benthic biodiversity	Mean monthly chl *a* (12 mo)	15 mg/m^2	10	11	36	62	-
	Max. chlorophyll *a*	50 mg/m^2	15	14	41	49	71
Trout habitat/angling	Max. chlorophyll *a*	200 mg/m^2	67	69	82	92	97
	Max. chlorophyll *a*	120 mg/m^2	33	42	59	79	92
Periphyton attribute, NPS-FM (NZ Government 2017)							
Band A	> 8% exceedance (1 of 12), chlorophyll *a*; based on monthly samples, for minimum of 3 years	<50 mg/m^2	41*				
Band B		50–120 mg/m^2	41				
Band C		120–200 mg/m^2	13				
Band D		>200 mg/m^2	5				
New Zealand Guideline for Cyanobacteria (Wood et al. 2009)							
Cyanobacteria alert	Max. cover, *Microcoleus*	20%	67	74	92	95	95
Cyanobacteria action	Max. cover, *Microcoleus*	50%	90	92	95	100	100

3.4 Discussion

3.4.1 Is there a problem with periphyton in Northland?

Returning to the question:

> *Is there a problem with periphyton in Northland (as determined from exceedances of MfE guidelines and breaches of the "national bottom line" (D band) of the periphyton attribute in the National Policy Statement for Freshwater Management (NPS-FM))?*

the analysis indicated that two sites (Hakaru at Topuni and Waiharakeke at Stringers Road) consistently exceeded the MfE guidelines in all years and also fell below the national bottom line of the NPS periphyton attribute. These two sites could therefore be defined as "problem sites". In particular, periphyton in the Hakaru at Topuni far exceeded the thresholds for all MfE guidelines and the NPS-FM bottom line.

Four of the five sites graded as band C of the of the NPS-FM periphyton attribute also exceeded the MfE guidelines for maintenance of ecosystem health in all years. The exception was Punakitere at Taheke, at which the MfE guidelines were met in 2017 but not in 2016. We also noted periphyton exceeded 200 mg/m^2 at least once in the monitoring period at all five sites graded as band C. Therefore, there is potential for these sites to fall into band D in other periods when flow conditions are different (see Section 3.4.2 below).

At the other end of the scale, over 80% of the 39 monitoring sites were graded as bands A or B of the NPS-FM, indicating that most sites in the region are not problematic in terms of nuisance periphyton as defined by current national guidelines.

More frequent exceedances of the MfE guidelines (Biggs 2000) partly reflect the facts that (a) the MfE guideline for mean chlorophyll *a* set for maintenance of biodiversity values (15 mg/m^2) is quite stringent; and (b) the MfE guidelines apply to any exceedances regardless of the time period considered (see Section 3.4.2 below). Nevertheless, two thirds of all sites exceeded the 15 mg/m^2 threshold when calculated over the whole monitoring period.

The seven sites graded as bands C or D of the NPS-FM periphyton attribute were not readily distinguishable from sites in bands A and B by environmental characteristics, including nutrients. Mean DIN at the two sites in band D was lower than the median value across all sites. Mean DRP was elevated at the two band D sites and at most band C sites (Figure 3-1, see Appendix B for site means). Ranges of other variables also overlapped, although band C and D sites had generally higher maximum temperatures and did not include any sites at which mean pH was less than 7 (Figure 3-1).

Both band D sites (Hakaru at Topuni and Waiharakeke at Stringers Road) were classified as SS geology in the REC. Sites graded as bands A, B and C had varied geology. Patterns associated with geology are explored further in Section 5.

Although cyanobacteria cover was recorded at over 80% of sites at least once, cover considered to be a problem occurred relatively infrequently, with most breaches in 2015. The four sites at which the Action level of the cyanobacteria guideline was exceeded (Kerikeri at Stone Store, Ruakaka at Flyger Road, Waiaruhe d/s Mangamutu Confluence, Waipapa at Waimate North Road) did not have problem periphyton based on the NPS-FM periphyton attribute (graded, respectively, in bands B, B, B and A).

3.4.2 Temporal variability and influence of river flows

The analysis of exceedances of the MfE guidelines in calendar years showed that 2015 was a “problem year”. Over 85% of sites monitored in 2015 exceeded the MfE guidelines for protection of biodiversity compared with 50% in 2017. Chlorophyll *a* exceeded 200 mg/m^2 at over 30% of sites in 2015, but at less than 8% of sites in 2017. Most of the exceedances of the Alert level of the cyanobacteria guideline occurred in 2015.

A comparison of river flow metrics (Figure 3.2) in hydrological years from 2014-15 to 2017-18 shows that the temporal pattern was likely attributable to lower than average frequency of large floods (>7 x median flow) in 2014-15 and 2015-16, and higher than average flood frequency in 2016-17 and 2017-18. The NPS-FM periphyton attribute integrates temporal variability by requiring a minimum of three years data for assessment of a site against the four attribute bands.

3.5 Summary of assessment

In summary, the periphyton data from 39 Northland sites indicates that a small proportion (5%) of sites have a periphyton “problem” (i.e., excessive periphyton) and a further 13% could potentially be problematic, when assessed against the NPS-FM. The rate of problem sites (graded as NPS-FM band D) was similar to that in a national dataset of 194 sites that included the sites from Northland, as well as from Bay of Plenty, Horizons region, Greater Wellington, Canterbury and Southland (Kilroy et al. 2019). Cyanobacteria cover exceeding guidelines affected 33% of sites. High cyanobacteria cover was persistent (occurring in three years) at only one site (Ruakaka at Flyger Road).

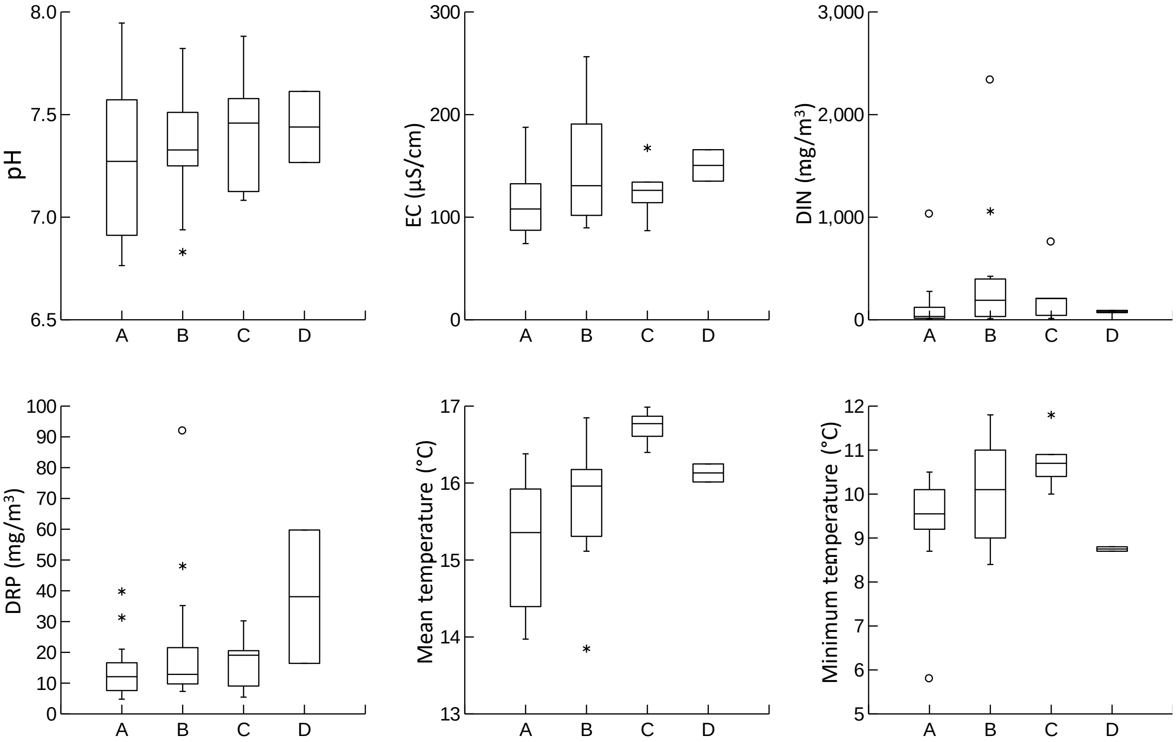

Figure 3-1: Box plots showing medians and ranges of pH, nutrients, EC and temperature at sites assigned to bands A to D of the periphyton attribute. Data from 2015 to 2018. DIN and DRP show geometric means. The line inside each box shows the median value; the box shows the range of the central 50% of all values, the whiskers show the values that fall within 1.5 times the range of the box. Asterisks and circles are outliers.

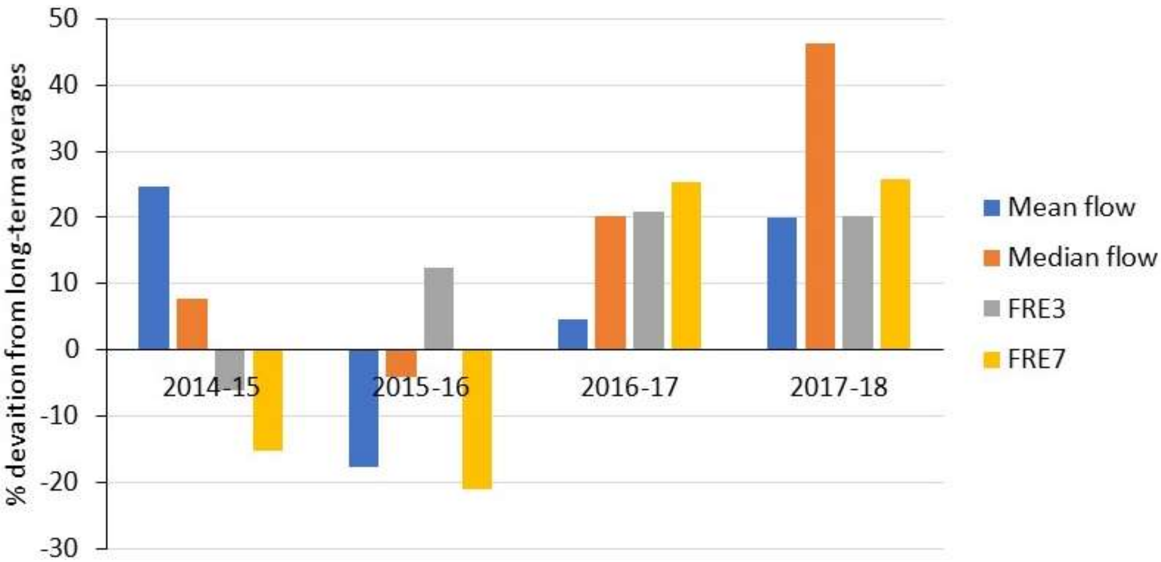

Figure 3-2: Comparison of deviations of hydrological metrics from the long-term mean in four years from 2014-15 to 2017-18. Years are hydrological years from July to June.

4 Drivers of periphyton biomass in Northland rivers: effect of river flows within sites

In the second objective of the project, NRC first asked:

What are the major drivers of periphyton growth in Northland?

The general answer to this question is well-understood from substantial national and international research into periphyton (e.g., Biggs 2000, Larned 2010). Therefore, our objectives in this section and the following section (Section 5) are to try to quantify the effect of the major drivers of periphyton in Northland rivers, using empirical methods based on the data from NRC's monthly periphyton dataset. In this section we provide brief background to controls on periphyton followed by an analysis of the data focussing on the effects of river flows.

4.1 Controls on periphyton in rivers: general background

Previous and ongoing national and international research has confirmed that periphyton abundance in rivers is primarily controlled by a combination of river flows and nutrient availability, and effects of flows and nutrients are mediated by a range of other factors.

- The overriding controller of periphyton abundance in rivers is often **river flow**. Periods of low, stable flows are associated with periphyton accrual, while high flows (with associated increased hydraulic forces) remove biomass through sloughing processes (Biggs and Close 1989, Hoyle et al. 2017) and prevent colonisation and accrual. An important metric is the magnitude of the flow at a site that is capable of removing accumulated biomass. In New Zealand a flow magnitude of 3 x median flow has been commonly adopted to represent the flow magnitude that typically removes periphyton. The widespread use of 3 x median flow for this purpose was based on the finding by Clausen and Biggs (1997) that FRE3 (the mean annual frequency of events exceeding 3 x median flow, Booker 2013) was the hydrological variable most highly correlated with a range of biological indices in New Zealand rivers. Clausen and Biggs (1997) did not explicitly explore periphyton accrual and removal, but FRE3 and its derivatives do appear to be appropriate for defining accrual periods in some cases. For example, Biggs (2000b) used 3 x median flow to calculate accrual period in rivers across New Zealand, and developed strong relationships between maximum chlorophyll *a* and dissolved N and P. However, recent analysis has confirmed the reasonable assumption that the flow magnitude required to removed periphyton to low levels differs between rivers (Hoyle et al. 2017). Analyses for periphyton data from the Canterbury and Horizons regions confirmed that using an empirically determined "effective flow" to calculate accrual period can improve predictability of peak periphyton (Kilroy et al. 2017, 2018).

- **Nutrient availability** is a primary determinant of the maximum carrying capacity of periphyton in a river, given suitable hydrological conditions in which to accrue. Nutrient availability is usually represented by concentrations of dissolved inorganic nitrogen (DIN) and dissolved reactive phosphorus (DRP) both of which vary over time and are themselves influenced (reduced) by periphyton growth though uptake. It is important to note that water column concentrations do not always reflect availability of nutrients but are used as a convenient surrogate for nutrient availability. The appropriateness of concentrations for representing nutrient availability varies from site to site, over time and with flow conditions. It is also noted that measures of total N (TN) (which include all organic and particulate N in a sample, in addition to the dissolved fraction) can be more strongly related to periphyton biomass than DIN.

- Other factors such as **light availability** and **temperature** affect algal growth rates and therefore biomass. In general, increasing light availability and temperature lead to increased growth rates. There are upper limits above which both high light and high temperature start to inhibit growth rates, but these limits are not normally attained in many rivers (Frost et al. 2005, DeNicola 1996). Fine **suspended sediment** can reduce growth potential by reducing light availability, and also by smothering algal mats when material settles out of the water column (Wagenhoff et al. 2011). Bed **substrate composition** can affect biomass by determining the area of riverbed available for colonisation by algae, and through the interaction between flow and substrate mobility, which affects potential for periphyton removal (Munn et al. 2010). Background **water chemistry** (e.g., conductivity, pH) may influence biomass via effects on periphyton community composition (Chetelat et al. 1999, Rott and Schneider 2014). Finally, **grazing by macroinvertebrates** can be an important biological control on periphyton biomass. The effects of grazing are variable but can be substantial (Liess and Hillebrand 2004).

4.2 Identification of an effective flow at each site

The aim of this part of the analysis was to identify, where possible, the flow magnitude (in multiples of the median flow) at each site that typically re-sets periphyton chlorophyll *a* to low levels. Here a "low level" refers to chlorophyll *a* equivalent to cover by thin algal films only (e.g., ~9 mg/m^2 on average, Kilroy et al. 2013), although the value is expected to vary across sites. The flow magnitude is subsequently referred to as the "effective flow" (hereafter EF). Once the EF is identified we can generate flow variables related to that flow magnitude for use in between-site analyses (Section 5). For example, useful variables for explaining differences in periphyton accrual and removal among sites are the mean annual frequency of flow events greater than the EF, and the mean time available for periphyton accrual between EFs.

Previous analyses have shown that thresholds cannot be identified for some sites (at least using the method below) (Kilroy et al. 2018). In other words, no single flow threshold is identifiable as the most effective at removing periphyton. However, assuming success in identifying EFs at sufficient sites, our objective was to compare the performance of hydrological predictors based on EF with those based on standardised flows (e.g., 3 x median) in general linear models for predicting peak chlorophyll a in Northland river.

4.2.1 Methods

We used all chlorophyll *a* data collected using the same methodology. Initially this was taken to include all data collected from 2013 onwards. However, examination of the plots (as part of the process outlined below) showed that in some cases patterns in 2013 and 2014 may have differed from those generated using only the monthly data from 2015 onwards. In particular, in the February and May surveys in 2013, all chlorophyll *a* was recorded as <2 mg/m^2 even though flows were relatively low from January 2013. The analysis was therefore repeated using only data from 2015 onwards, as we considered that the monthly data were more consistent with the flows.

We identified effective flow thresholds (as chlorophyll *a*) in the following steps:

1. Calculate the median flow at each site using a 10-year flow record (from 2008 to the present), or as long a record as was available.

2. Extract from each flow record time series of daily mean and maximum flows.

3. Using the daily time series extract for each periphyton observation (from dataset A in Section 3.3) the number of days since flows that equalled or exceeded a range of multiples of median flow, N_m, based on the median flow calculated in step 1.

4. The range of N_m used in this analysis was 1.5, 2, 3, 4 …. up to 20 x median flow.

5. Using dataset A (see Section 3.3) (with variables added for the days since the event of each magnitude, both as daily means and daily maxima), fit a series of linear regressions at each site between chlorophyll *a* and time since each defined high flow. Use $\log_{10}$-transformed data.

6. The N_m associated with the linear regression that explained the highest proportion of variance in periphyton chlorophyll *a* was generally taken as the potential EF.

7. Reconfirm or adjust the automated selection of flow magnitude by examining (a) all the relationships (as scatter plots) and (b) plots of R^2 against flow magnitude. Under (a) look at the slope and intercept as well as R^2. The slope may indicate accrual rates at different sites. The intercept indicates low chlorophyll *a* when accrual time = 0.

8. Sites at which no relationship explained more than ~20% of the variance in chlorophyll *a* were generally judged as having no identifiable EF. At these sites, R^2 tended varied little across the range of multiples of median flow.

The number of days since a high flow event is potentially the accrual time available for periphyton development, assuming that smaller flow perturbations during that time have only a minor effect on biomass. Relationships in which accrual time explains a high proportion of the variability in chlorophyll *a* indicate that the flow threshold defining the accrual time approximates the threshold that removes periphyton to low levels.

This method isolates the EF because if N_m is too low, high chlorophyll *a* could occur after short accrual times because some high flows would fail to remove biomass, leading to low explanatory power; if the selected flow size is too high, then low chlorophyll *a* could occur after long accrual periods after being removed by smaller flows, again leading to low explanatory power. Only at flow sizes close to the threshold for removal do we expect a strong correlation between chlorophyll *a* and days since the high flow, with the slope of the relationship approximating the rate of accrual at that site. We also expect the relationship intercept to be close to zero, indicating that chlorophyll a at zero accrual period is also close to zero.

A caveat to the method is that spontaneous sloughing after long accrual periods can lead to unexpectedly low biomass (Biggs and Close 1989). It is also acknowledged that the condition of the periphyton can influence the effect of a particular high-flow event (Katz et al. 2018). For these reasons, and acknowledging other influences on periphyton within a site, the accrual period – chlorophyll *a* relationships are not expected to have very high explanatory power (e.g., > 70%). However, the general pattern should be evident from plots of the data. In this analysis our approach was to make the final selection of an EF after examining for each site the plots $\log_{10}$ chlorophyll *a* vs. $\log_{10}$ time since high flows and the relationship between R^2 and multiples of median flow.

4.2.2 Results

Using all data from 2015 onwards, we identified the magnitude of the EF at 16 of the 21 sites with a flow record. These are the "flow-sensitive" sites in Table 4-1. The EF ranged from 2 x to 19 x median flow, and the time since an event exceeding the EF explained from 18% to 61% of the variance in chlorophyll *a*, with an average of 35%. The slopes of the relationships varied from 0.35 to >1, and the intercepts were all < 1 (i.e., less than 10 mg/m^2 chlorophyll *a* when the accrual period = 0).

At the remaining five sites (the "flow-insensitive" sites in Table 4-1), the relationships were weak (R^2 < 0.15) and varied little over the whole range of thresholds.

The difference between flow-sensitive and flow-insensitive sites can be seen easily on plots of R^2 against flow thresholds (Figure 4-1).

Table 4-1: Summary results of analysis of chlorophyll *a* versus accrual times at 21 sites with a flow record, with assignments of effective flow. In all cases except one, the selected relationship was the one with the highest R^2. The exception was Opouteke at Twin Bridges where two relationships were similar and the one corresponding to the lower flow threshold was selected even though R^2 was marginally lower.

		Selected relationship		
Periphyton site	**EF**	**R^2**	**Slope**	**Intercept**
Flow-sensitive sites				
Punakitere at Taheke	1.5	0.32	0.56	0.77
Waitangi at SH10	2	0.21	0.50	0.01
Mangakahia at Twin Bridges	3	0.40	0.65	0.48
Waiharakeke at Stringers Road	3	0.61	1.01	-0.02
Kaihu at Gorge	5	0.17	0.28	0.99
Otaika at Otaika Valley Road	5	0.56	0.73	0.07
Ruakaka at Flyger Road	6	0.36	0.52	0.34
Waiarohia at Second Avenue	6	0.28	0.44	0.76
Waitangi at Waimate North Road	6	0.51	0.84	-0.73
Raumanga at Bernard Street	7	0.28	0.55	0.11
Victoria at Victoria Valley Road	7	0.38	0.68	-0.19
Awanui at FNDC	8	0.34	0.82	0.25
Ngunguru at Coalhill Lane	8	0.44	0.82	-0.19
Waipapa at Forest Ranger	13	0.41	0.56	-0.13
Opouteke at Suspension Bridge	17	0.21	0.40	0.80
Kerikeri at Stone Store	19	0.18	0.35	0.80
Flow-insensitive sites				
Hatea at Mair Park	2	0.06	-0.16	1.04
Hakaru at Topuni	5	0.01	0.12	2.04
Mangahahuru at Main Road	5	0.14	0.20	0.63
Waipao at Draffin Road	9	0.10	0.35	0.31
Waipoua at SH12	9	0.10	0.17	0.19

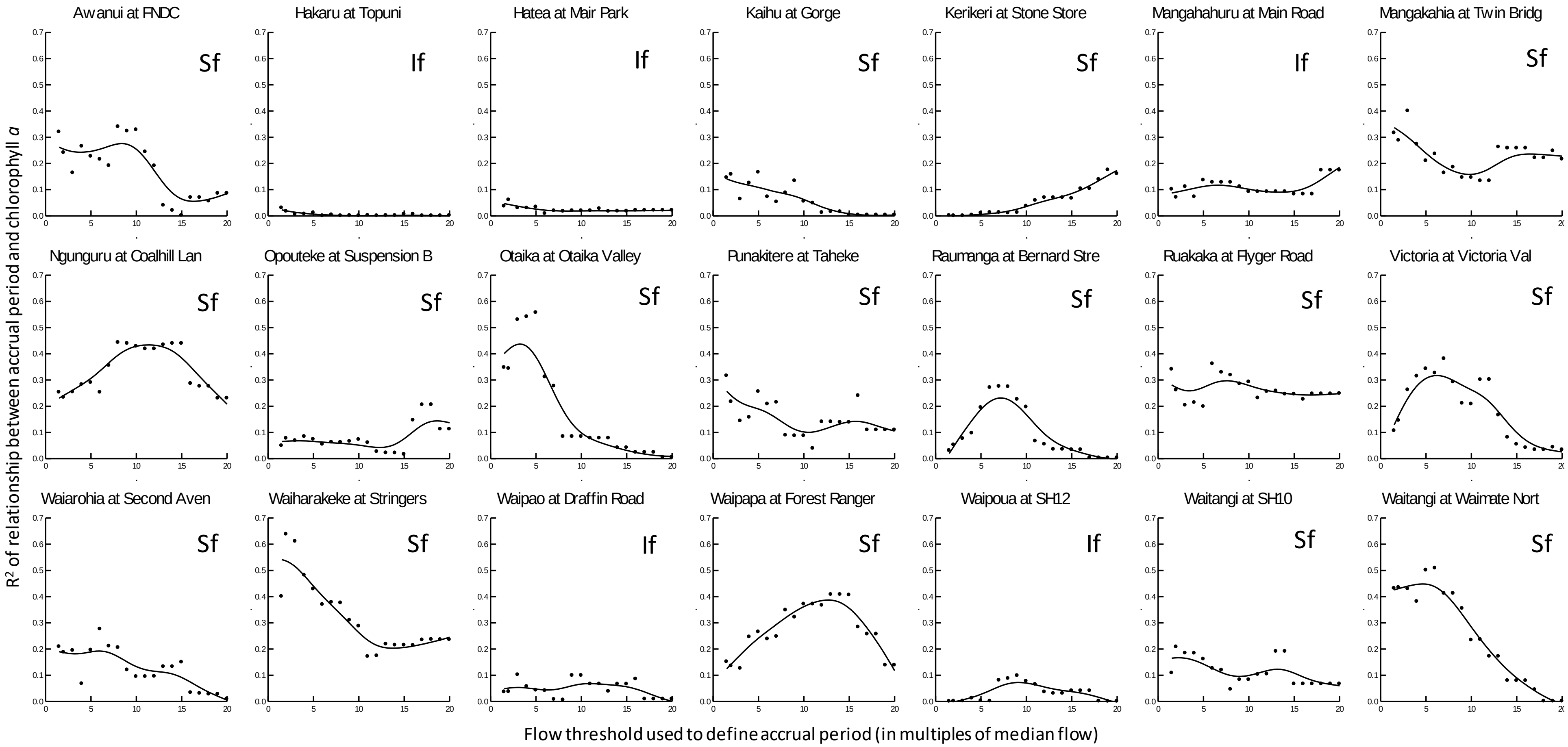

Figure 4-1: Plots of R^2 versus flow threshold for defining accrual period (in multiples of median flow) at each of the 21 NRC sites with a flow record. Distance weighted least-squared lines are fitted through the points to show the general shape of the relationships. Flow-sensitive sites (Sf) have a reasonably well defined maximum R^2, with $R^2 > 0.2$ in most cases. Flow-insensitive sites (If) have consistently low R^2 across the whole range of flow thresholds, and clear relationships were not evident in plots of chlorophyll *a* versus accrual time. Note that some cases of increasing R^2 at high flow thresholds occurred because positive relationships turned to negative relationships.

An example of accrual time based on EF with low explanatory power was Opouteke at Suspension Br (Figure 4-2). Accrual period based on 17 x and 18 x median flow had highest R^2 (0.20). The slopes and intercepts of these relationships were almost identical and the lowest threshold was selected. At lower thresholds, the slopes and R^2 values were consistently lower.

The strongest relationship was detected at Waiharakeke at Stringers Road, where accrual time based on 3 x median flow explained 61% of the variance in chlorophyll *a* (Figure 4-3).

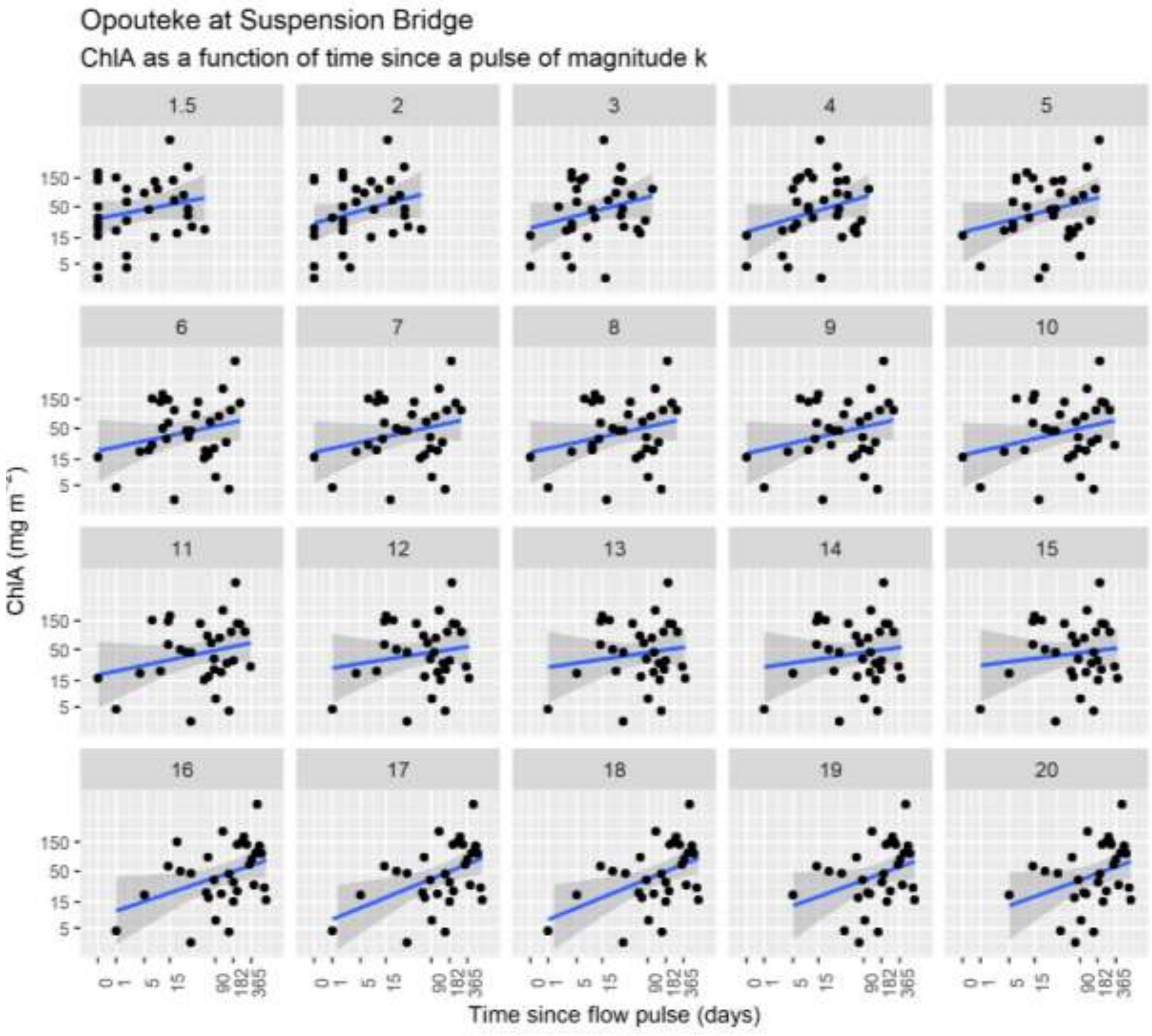

Figure 4-2: Chlorophyll *a* plotted against time since flow pulses at Opouteke at Suspension Bridge. All data since 2015 were included. Flow pulses were defined as multiples of the long-term median flow calculated from daily mean flows from 2000 (or later if the record started after 2000) to 2018.

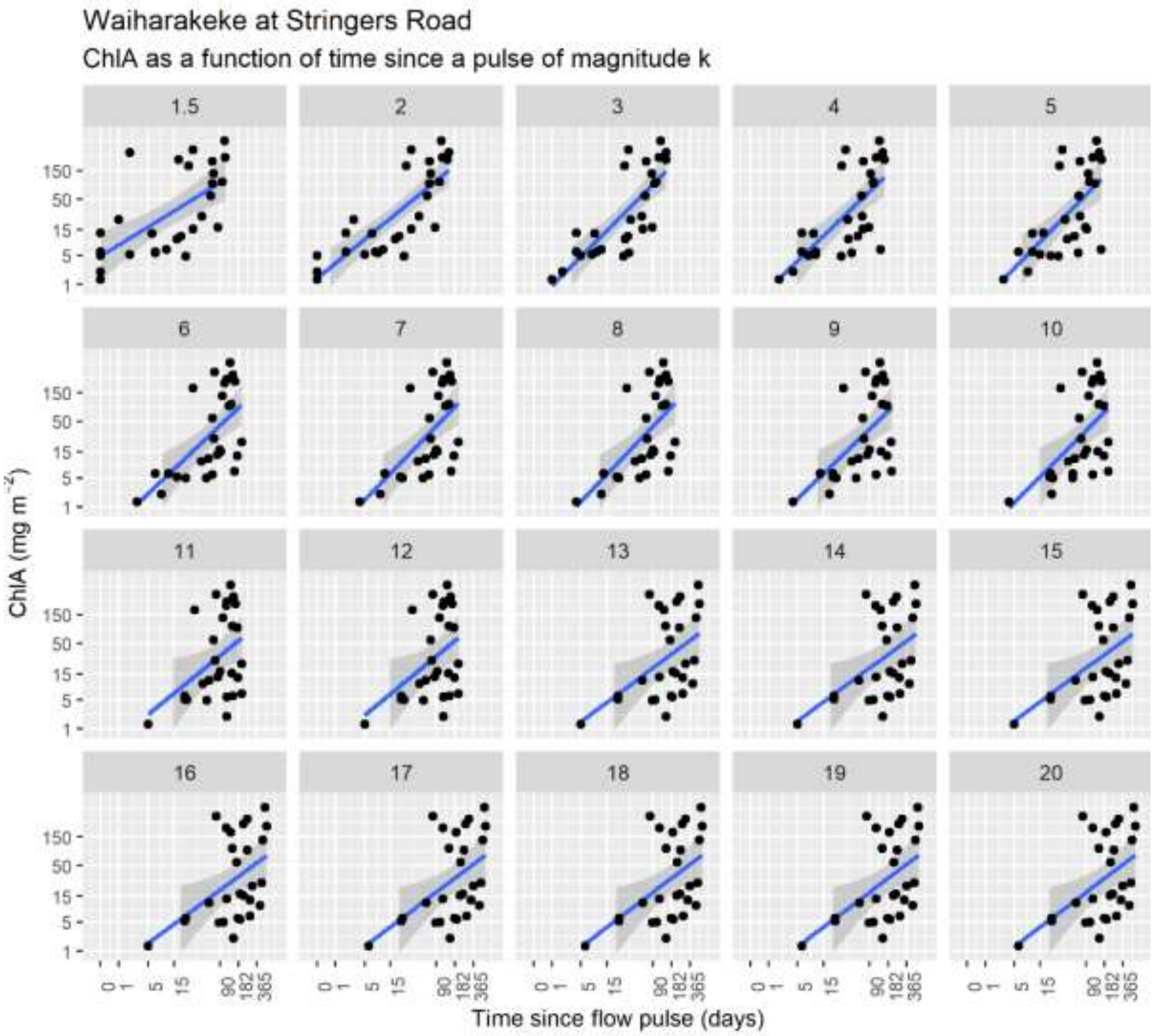

Figure 4-3: Chlorophyll *a* plotted against time since flow pulses at at Waiharakeke at Stringers Road All data since 2015 were included. Flow pulses were defined as multiples of the long-term median flow calculated from daily mean flows from 2000 (or later if the record started after 2000) to 2018.

4.3 Discussion

4.3.1 Identification of effective flows

The magnitude of the flow that removes periphyton can be estimated empirically using a range of methods in addition to the one used above. For example, Hoyle et al. (2017) identified EF at 18 sites in the Horizons region by plotting chlorophyll *a* against the maximum daily flow in the 7 days prior to each chlorophyll *a* observation. The EF was taken as the flow threshold above which chlorophyll *a* was below a specified level (e.g., 10 mg/m^2) in at least 95% of cases. We expect that all empirical methods would converge to a similar flow magnitude because all have the same objective of determining a flow magnitude that results in low chlorophyll *a* following the event and, usually, higher chlorophyll *a* as the flood-free period (accrual period) is extended.

Hoyle et al. (2017) found that using maximum daily flows produced a clearer result than using mean daily flows. Mechanistically this makes sense because observations from laboratory experiments indicate that most periphyton removal occurs as soon as the critical velocity is attained (Biggs and Thomsen 1995, Francoeur and Biggs 2006). The experimental findings thus implied that short-lived peaks that make little difference to daily mean flow may remove periphyton. On the other hand, in large floods, most periphyton could be removed long before peak flow is reached. In the present analysis we found that using daily mean flows and daily maximum flows produced similar results. We chose to use daily mean flows because the flow metric is simpler and because previous analysis showed that the regression results were slightly stronger (on average) (Kilroy et al. 2019).

We expected substantial unexplained variation in the relationship between accrual period and chlorophyll *a* because chlorophyll *a* is influenced by many variables other than flow. Furthermore, seasonality was not considered (i.e., expected higher growth rates in warm summer temperatures). Nevertheless, the overall mean R^2 of 0.35 across Northland flow-sensitive sites was lower than that found in other regions. For example, mean R^2 across 24 Canterbury sites was 0.55 (Kilroy et al. 2019). Low explanatory power of the relationships in Northland may suggest that flood frequency and accrual period may not exert as strong an influence on periphyton in Northland as in other parts of New Zealand.

5 Drivers of periphyton biomass in Northland rivers: relationships between chlorophyll *a* and multiple environmental variables

In this section, we continue to address the question asked by NRC (*What are the major drivers of periphyton growth in Northland?*) by considering the role of other variables that influence periphyton, in combination with flows. NRC also asked the following question:

> *In particular, what are the roles of dissolved inorganic nitrogen (DIN), dissolved reactive phosphorus (DRP) and ammoniacal-N (NH4-N) in driving periphyton and what are appropriate instream nutrient criteria for Northlands hard-bottomed rivers?*

In addressing the first part of this question, the following assumptions were made:

1. Periphyton refers to peak periphyton measured as chlorophyll *a*, where the peak (or maximum) represents carrying capacity at a site over the monitoring period. Peak periphyton was represented by the 92nd percentile of chlorophyll *a* calculated over the 42-month dataset (i.e., Chla_92) as required for assessments against the periphyton attribute of the NPS-FM (see Table 3-1).
2. To determine the roles of DIN and DRP as drivers of periphyton in Northland, we would need to account for other potential controllers of periphyton, such as flows, temperature and substrate.

The analysis was conducted in three steps.

- Step 1 included defining potential predictors of chlorophyll *a* and also defining categorical variables that could be used to partition the sites into groups that may show more consistent periphyton – environment relationships than the entire dataset.
- Step 2 was to check relationships between chlorophyll *a* and single predictors.
- Step 3 was to explore relationships between chlorophyll *a* and combinations of largely uncorrelated[3] predictors.

Steps 2 and 3 both included investigating the effect of partitioning the sites (on the basis of the variables defined in step 1) on the relationships.

A fourth step was to determine nutrient criteria for Northland rivers. Step 4 depended on identifying appropriate relationships in Step 3 and is covered in Section 6.

5.1 Predictor variables

The variables provided in the Northland periphyton and water quality dataset considered relevant as predictors, and having sufficient data, are listed in Table 5-1 along with justification for their inclusion. Dissolved oxygen (as ppm or %) were not included as DO is more likely to change in response to periphyton rather than affect periphyton.

DIN was calculated as the sum of nitrate-nitrite nitrogen (NO_x-N) and ammoniacal nitrogen (NH_4-N). NH_4-N usually forms a minor fraction of DIN (on average 3% across a range of New Zealand rivers, Kilroy 2016). Low concentrations of DIN (< 45 mg/m^3) may comprise much higher proportions of NH_4-N (up to 70%) although low DIN can also be predominately nitrate nitrogen (NO_3-N) (Kilroy

[3] Uncorrelated was defined as having a Pearson correlation coefficient of <0.5. This generally translates to less than 20% of the variance in one variable explained by the other. Most of the coefficients were much lower than this.

2016). Northland rivers included in the present dataset had relatively high proportions of NH_4-N in DIN (average of 20%, range <2% to >50%) across a range of DIN. NRC specifically requested for the effect of NH_4-N on periphyton to be considered in the analysis. Therefore, two variables based on NH_4-N were included as predictors (Table 5-1).

Table 5-1: Dependent and predictor variables used in the analysis, with justification for inclusion of each. Under TF (transformation), sqrt = square-root.

Group	Variable name	Units	Metric	Abbreviation	TF	Explanation / notes
Dependent variable						
Periphyton	Chlorophyll *a*	mg/m^2	92nd percentile	Chla_92	log_{10}	Metric used in NPS-FM to represents peak potentially "nuisance" periphyton chlorophyll *a* calculated across several years; adjusted to compensate for missing values
Explanatory (predictor) variables						
Temperature	Water temperature	°C	Mean	Tmean	none	Water temperature determines growth rates in periphyton, which may be reflected in biomass. The temperature – growth rate relationship is expected to be generally positive within the range of temperature in NZ rivers.
			Minimum	Tmin	none	
			Maximum	Tmax	none	
Nutrients	Dissolved inorganic N	mg/m^3	Geometric mean	DIN	log_{10}	Nutrients essential for periphyton growth. Geometric mean down-weights the influence of occasional high spikes. DIN was calculated as nitrate + nitrite-N (NO_x-N) + NH_4-N. NH_4-N is assimilated by algae in a process different from that for NO_3-N. Concentrations and proportions of the two N sources may lead to different growth rates, biomass and community composition (Kilroy 2016). TN and TP are often better predictors of periphyton than DIN and DRP. One reason for this is that TN and TP reflect periphyton abundance because they include sloughed algae in the water column (i.e., circular reasoning). Ratios may indicate which nutrient is driving growth.
	Dissolved reactive P	mg/m^3		DRP	log_{10}	
	Ammoniacal N	mg/m^3		NH4N	log_{10}	
	Percentage NH_4-N	%	Mean	pcNH4	sqrt	
	Total N	mg/m^3	Geometric mean	TN	log_{10}	
	Total P	mg/m^3		TP	log_{10}	
	Ratios of N to P	ratio		DINtoDRP	log_{10}	
				TNtoTP	log_{10}	
Water chemistry	Electrical conductivity	µS/cm	Mean	EC	sqrt	EC is a measure of concentration of ions in water and may influence periphyton biomass through the influence of minor nutrients (Ca, Mg). pH can affect species composition.
	pH		Mean	pH	none	
Suspended sediment	Water clarity	m	Mean	Clarity	none	Clarity and turbidity affect periphyton through their effect on light availability and through indicating potential for fine sediment deposition, which smothers algae
	Turbidity	NTU	Geometric mean	Turbidity	sqrt	

Group	Variable name	Units	Metric	Abbreviation	TF	Explanation / notes
Substrate	Percent coarse	%	Mean	Pccoarse	none	Bed substrate composition generally determines stability of the bed. Periphyton tends to accrue for longest on large stable substrates, and has short accrual times on small, mobile substrate.
	Percent fine			Pcfine	none	
	Percent sand			Sand	sqrt	
Flow	Mean flow	m^3/s	Mean	Meanflow	$\log_{10}$	
	CV of flow	%		CV_flow	sqrt	Flow variability controls removal of periphyton through scouring. Periphyton in large and small rivers may respond differently to similar magnitude high flows.
	Reversals	No./y		Reversals	none	Mean annual number of times flow reverses from declining to increasing or vice versa.
	Nneg	days		Nneg	none	Mean annual no. days when flow is less than on the preceding day.
Accrual	Accrual period based on different flows	days	Mean	Da3, Da7, Da13, DaEF	$\log_{10}$	Mean interval in days between successive high flows exceeding a specified threshold. Accrual represents the average time available for biomass to accumulate.

Geometric means were calculated for nutrient variables and turbidity to down-weight the effect of high outlier values. The geometric mean is similar to the median. Transformations were applied to the averaged data where data across sites were skewed or non-normally distributed.

At each site where an EF was identified (Section 4) we calculated a mean accrual period based on EF:

$$DaEF = (365 - \text{mean annual no. days flow} > EF) / FRE\_EF \qquad \text{(Equation 1)}$$

where FRE_EF is the mean annual frequency of events exceeding EF, with a 5-day window (i.e., events occurring 5 days or less apart were counted as a single event). Accrual period at each site was also calculated based on 3, 7 and 13 x median flow (Da3, Da7, Da13) using the method above.

We tested the effect on relationships of classifying the sites based on four categorical variables, summarised in Table 5-2.

The classifications included mean upstream catchment slope, extracted from data linked to the REC network. Snelder (2015) suggested that mean upstream slope could be used as the basis for defining water quality FMUs in the Northland region. Although the proposal was not adopted in Northland’s proposed regional plan, we considered that a trial of the effect of partitioning sites using the Snelder (2015) proposal was useful in view of likely effects of river slope on factors that influence periphyton biomass (e.g., upstream geomorphology, Hoyle et al. 2017; water velocity, Francoeur and Biggs 2006). The threshold of 10 degrees is somewhat arbitrary but nevertheless separates sites with low gradient catchments (Lowland sites) from those with higher gradient catchments (Hill sites).

Table 5-2: Classifications used to partition sites. The 39 sites were subdivided into groups based on these classifications, to see whether stronger or different periphyton – environment relationships were associated with different types of sites. Numbers of sites in each class shown in parentheses. For geology, HS = hard sedimentary; SS = soft sedimentary; VA = volcanic acidic.

Classification	Classes			Derivation
Flow	Flow-sensitive (16)	Flow-insensitive (5)	No flow data (18)	Analysis in Section 4 of this report, Table 4-1.
Geology	HS (9)	SS (9)	VA (20)	REC geology classes (HS, SS, VA) (Snelder and Biggs (2000)
Shade	Full sun (23)	Partial shade (14)	Shaded (1)	NRC-assigned categories (no shade category for Mangakino).
Mean upstream slope	Lowland (16)	Hill (22)		Based on usslope variable linked to REC. Lowland <10 degrees; Hill > 10 degrees (Snelder 2015)

5.2 Relationships between chlorophyll *a* and single predictors

5.2.1 Methods

Correlations between the 92nd percentile of chlorophyll *a* (Chl_92) and the nutrient variables (DIN, DRP, NH4N, pcNH4, TN and TP) were recalculated after subdividing the sites based on site and catchment features that could affect chlorophyll *a*. Site-specific features were shade (categories provided by NRC), effects of flow (the categories defined following the analysis in Section 4), geology (REC1 geology categories) and upstream catchment slope (as defined by Snelder 2015).

TN and TP were included because TN and TP often show stronger relationships with periphyton biomass than DIN and DRP (e.g., Dodds 2003). Data were plotted, and potentially interesting relationships were followed up in the multi-variable analysis.

5.2.2 Results

Across all sites, Chl_92 was not strongly correlated with any of the nutrient variables. Refer to Appendix B for the complete matrix. Correlations between Chla_92 and nutrient concentrations were positive but weak ($r < 0.4$). TN and TP were slightly more strongly correlated with Chla_92 than, respectively, DIN and DRP (Appendix B).

Effect of sensitivity to flow

Flow-sensitive sites showed no relationship with nutrient concentrations. However, Chla_92 at the five sites identified as insensitive to flows was strongly correlated with DRP and TP and also NH4N, but not DIN, TN or pcNH4 (Figure 5-1).. DRP, TP and NH4N were strongly intercorrelated across these sites. Therefore potential drivers of Chla_92 were unclear.

Effect of geology

The NRC periphyton sites covered three REC geology classes (Table 5-2). The slope of the correlation between all nutrients and Chla_92 was higher for sites within the HS class (see Table 5-2) than in the other two classes (Figure 5-3). DIN, TN and TP explained over 40% of the variance in Chla_92 across the nine sites with HS geology, and DRP explained 20%. In contrast, the nutrient variables explained

<1% of the variance in Chla_92 across SS and VA classes, except for TN and TP which explained, respectively, 12% and 7% of the variance in in Chla_92 across the SS class.

Effect of shade

Plotting Chla_92 against DIN, DRP, TN and TP with sites partitioned into full sun and partial shade sites (with just one shaded site, Ruakaka at Flyger Road) showed no relationship between nutrients and chlorophyll *a* at full sun sites, but possible (although weak) relationships at partial shade sites. The five sites with lowest Chla_92 were all in the partial shade group (Figure 5-1). This group included sites with high Chla_92, suggesting that sites in the category span a wide range of light conditions.

Effect of upstream slope

The plots in Figure 5-4 suggest that sites in the Hill category have different relationships between Chla_92 and DIN or TN from those at sites in the Lowland category. In particular, TN explained 21% of the variance in Chl_92 across Hill sites, but 0% at Lowland sites. There was also a difference between the two categories in the Chla-92 relationship with DRP (12% explained at Lowland sites and 0% explained at Hill sites). The plots also highlighted that DIN, TN and NH4N were all generally higher at Lowland sites than Hill sites, and pcNH4 was higher at Hill sites than at Lowland sites (confirmed by two-sample t-tests, $P < 0.001$). Such differences between Hill and Lowland sites were not seen in DRP or TP (two-sample t-tests, $P > 0.2$).

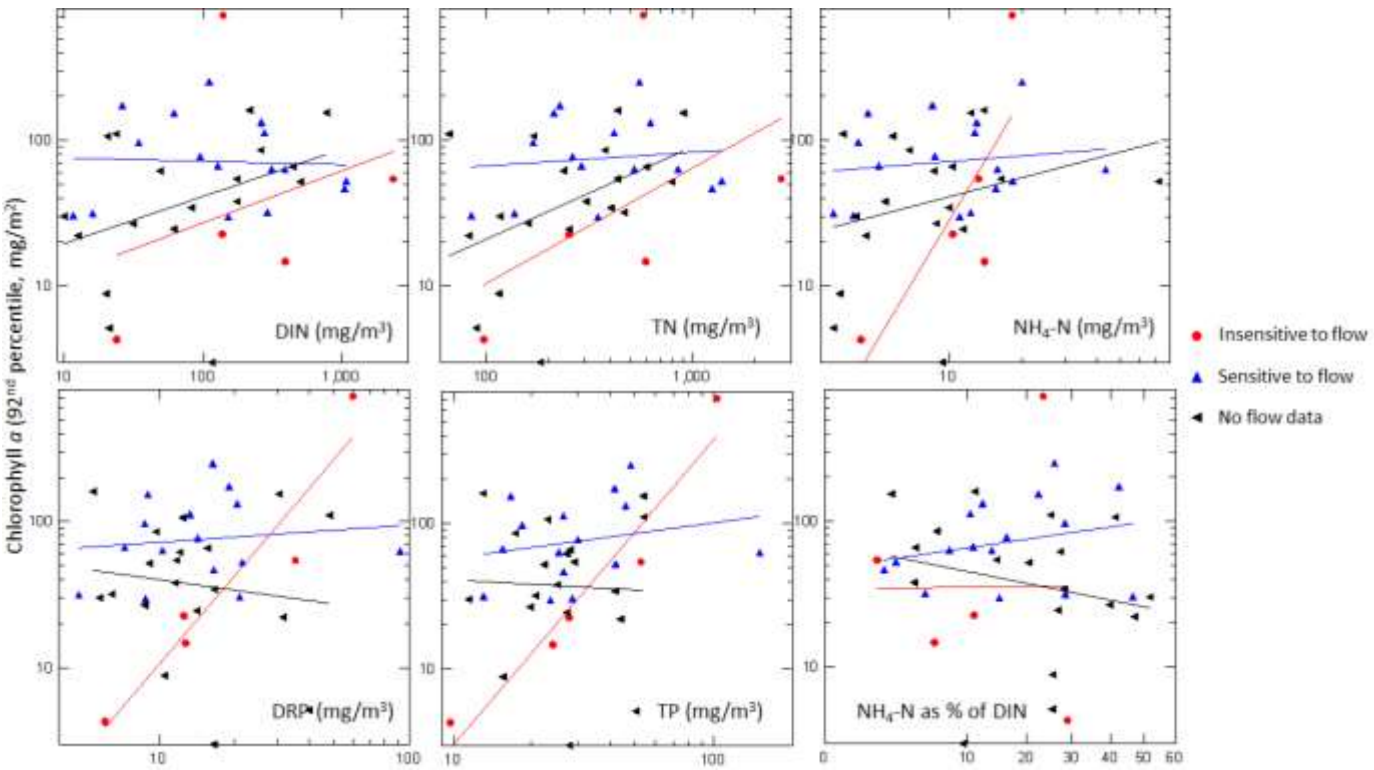

Figure 5-1: Plots of chlorophyll *a* versus DIN, DRP, TN, TP, NH4N and pcNH4 with sites partitioned into flow sensitive and flow insensitive sites. Sites with no flow data are also shown, although there is no basis for expecting any relationship or lack or relationship with nutrients across these sites.

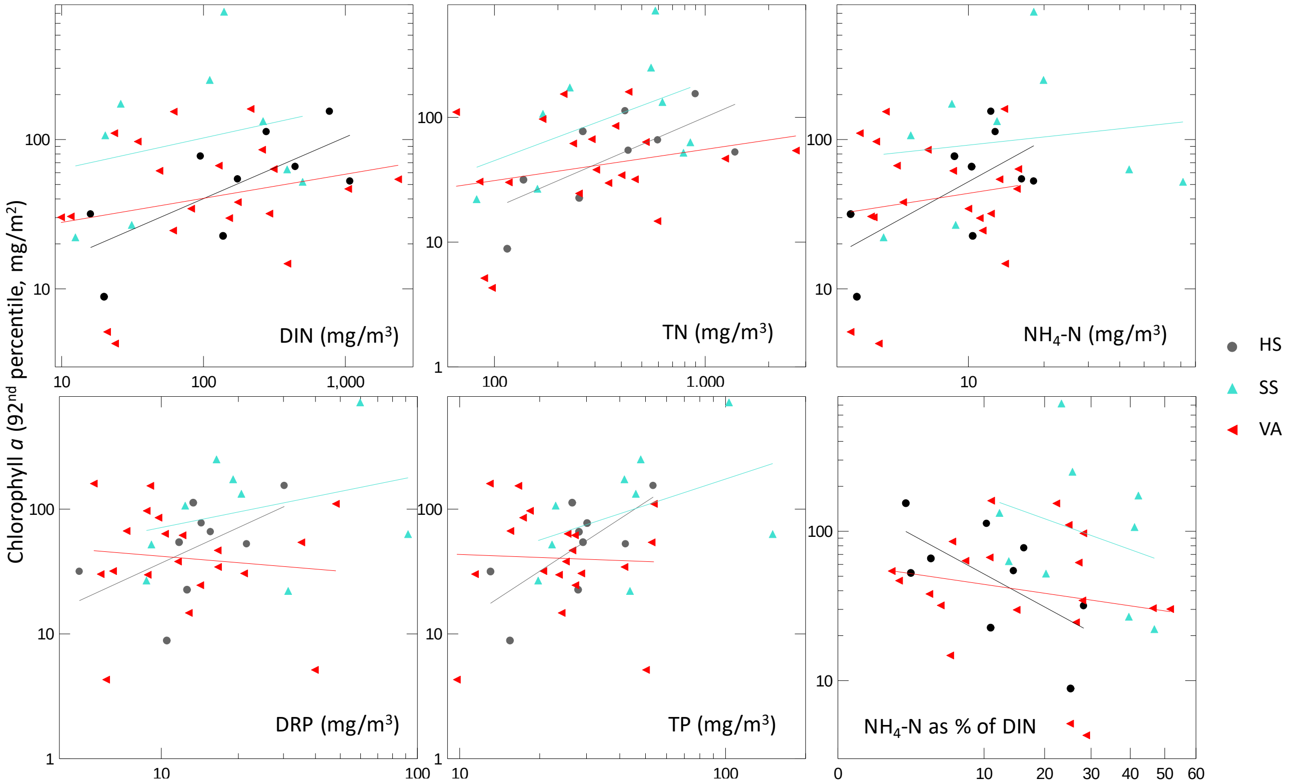

Figure 5-2: Plots of chlorophyll *a* versus DIN, DRP, TN, TP, NH4N and pcNH4 , with sites partitioned according to their REC geology class.

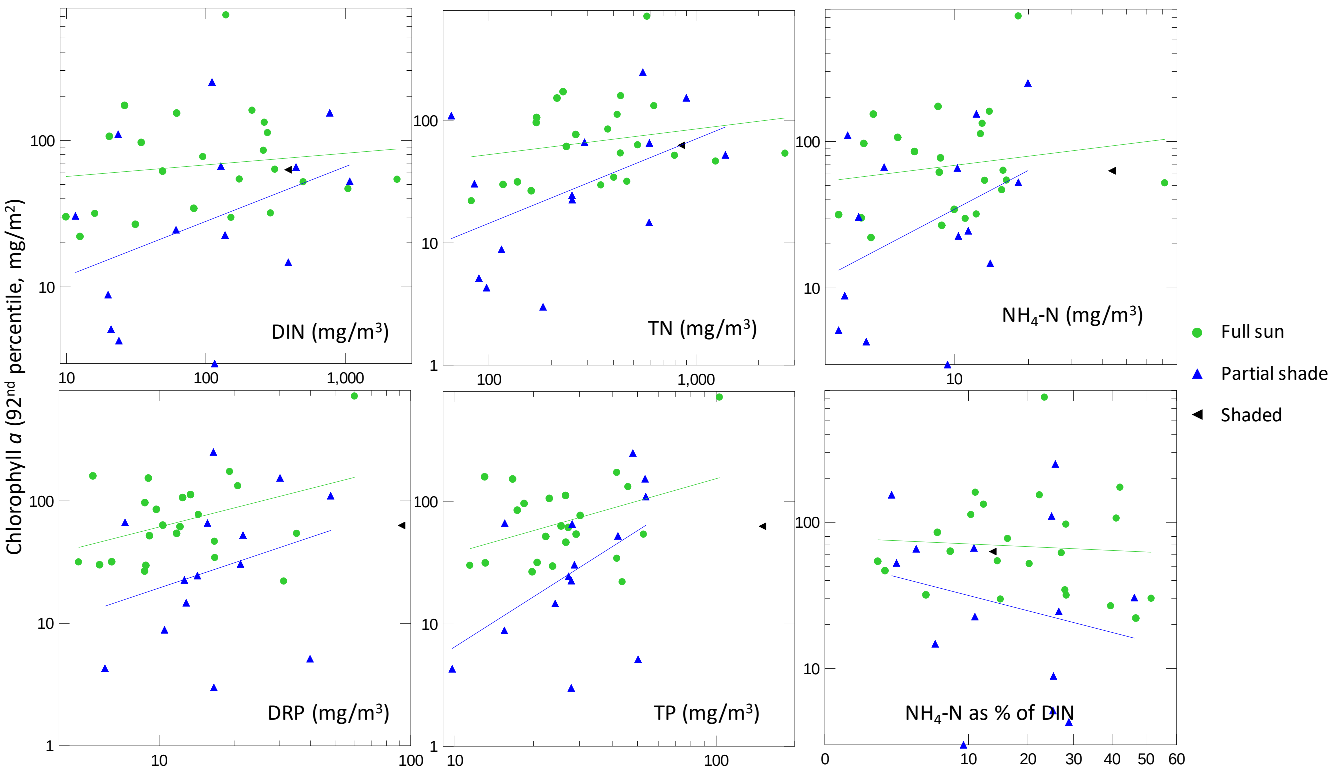

Figure 5-3: Plots of chlorophyll *a* versus DIN, DRP, TN, TP, NH4N and pcNH4 , with sites partitioned into full sun and partial shade sites.

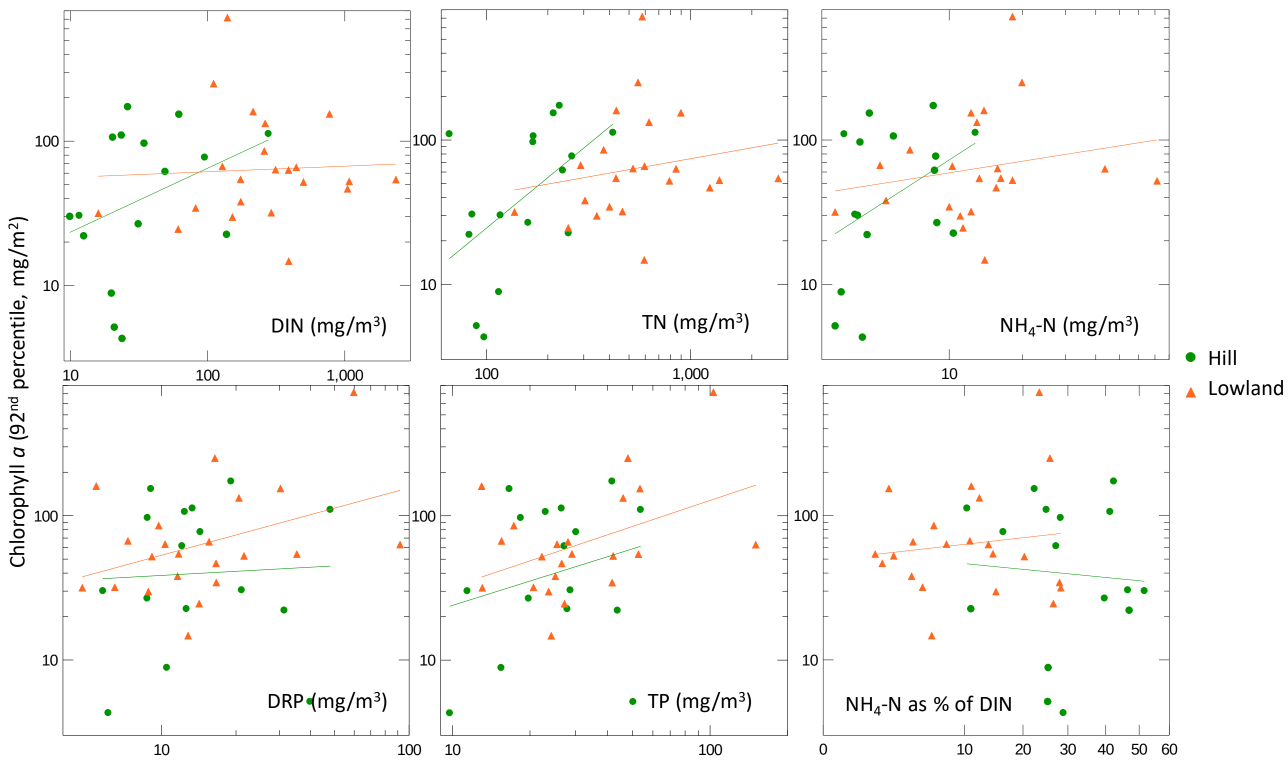

Figure 5-4: Plots of chlorophyll *a* versus DIN, DRP, TN, TP, NH4N and pcNH4 , with sites partitioned into Hill and Lowland sites based on mean upstream slope. Hill and Lowland classes defined as in Snelder (2015).

5.3 Relationships between chlorophyll *a* and multiple predictors

5.3.1 Methods

Data preparation and model screening

Dataset B (see Section 2.5) were used for the analysis (i.e., data averaged over the entire monthly time-series) with Chla-92 (adjusted to account for missing values) as the dependent variable, for consistency with the metric used in the periphyton attribute of the NPS-FM (NZ Government 2017).

A Pearson correlation matrix was run on all the variables listed in Table 5-1 using dataset B (i.e., the combined data from the complete time-series of data from the 39 periphyton sites, as defined in Section 2.5). Only one variable of pairs that were strongly correlated (r > 0.6) in the Pearson correlation matrix (Appendix B) was retained within the same model. Excluded variables were:

- Tmax (correlated with Tmean);
- Clarity (correlated with turbidity [negative] and DaEF [positive]);
- Pcfine (correlated with both Pccoarse [negative] and Pcsand);
- DINtoDRP and TNtoTP (correlated with, respectively, DIN and TN);
- pcNH4 (correlated with DIN and TN [negative]);
- NH4N (correlated with DIN and TN [positive]);
- TN and TP (correlated with, respectively, DIN and DRP).

Models were run including either DIN and DRP or TN and TP, but not both. Models including pcNH4 or NH4N did not include DIN or TN.

The regressions were performed first using all of the available data and then on subsets of sites based on chlorophyll *a* response to flow, REC geology class, shade category and catchment slope (Table 5-2). When EC was included as a predictor, we omitted the two sites identified as tidally influenced (Hatea and Kerikeri, see Section 2.5).

All data were first checked for normality and homoscedasticity and, if necessary, were transformed prior to analysis (Table 5-1). The data were screened by plotting all potential predictor variables against the dependent variables to look for obvious departures from linear relationships such that a polynomial term might need to be included. None were detected.

We used an information-theoretic (IT) model selection procedure (Whittingham et al. 2006) on dataset B to identify promising models in each set of sites and available variables. The IT procedure identifies all the best subsets of models given a selection of predictor variables and ranks them on the basis of a range of model evaluators including R^2, the Akaike Information Criterion (AIC), and Mallows C_p (refer to Geyer 2003 for information on each). Our aim was to identify strong relationships that used the minimum number of variables, so that the final models were not "over-fitted", given the relatively small size of the datasets. The ranking procedure was performed using the "best subsets" routine in SYSTAT v. 13.

The residuals of promising models were examined to see whether adding polynomial terms (which represent non-linear relationships) could improve the model fit. We did not consider interaction terms in this analysis in order to avoid overfitting models on the small datasets. Before accepting models derived from subsets of sites as promising, the variance inflation factors (VIF) associated with each set of predictor variables were examined. VIFs indicate whether predictors are correlated with each other (i.e., multicollinearity). A general rule-of-thumb is that VIF > 4 indicates collinearity that might affect the stability of the model and such models need to be examined to determine whether excluding variables is justified (O'Brien 2007).

Model development and validation

Promising relationships identified in the IT selection procedure were re-run using the GLM package in R. The fit of each model in each dataset was assessed using **leave-one-out cross-validation** (Picard and Cook 1984). In this procedure, the independent (predictor) variables are used to generate a series of models omitting one data point each time. Each model is used to predict the value of the dependent variable for the omitted data point. Observed values are plotted against predicted values and statistics can be computed to allow assessment of the model fit (i.e., accuracy and precision):

- the coefficient of determination, R^2, which is a measure of the proportion of variance in the observed values explained by the predicted values;
- the root mean square deviation (RMSD), which is an absolute measure of the difference between predicted and observed values, in the same units as the dependent variable (i.e., $\log_{10}$chlorophyll *a*). The lower the value the better;
- Nash Sutcliffe Efficiency (NSE), which is commonly used to assess predictive skill in hydrological models (Nash and Sutcliffe 1970).[4] NSE ranges from -∞ to 1, where the

[4] NSE is calculated in the same way as R^2 except that NSE uses the sum of squares of observed – independently predicted values (such as from leave-one-out cross validation), whereas R^2 uses the sum of squares of the observed value – the value estimated from the regression

closer the number is to 1, the better model fit. NSE = 1 indicates perfect model fit, 0 indicates that model predictions are as accurate as the mean of the observed data and negative values indicate that the mean is a better predictor than the model. NSE is generally proportional to R^2 but is specifically used to quantify how well a model simulation predicts the outcome variable. As well as testing the correlation between observed and predicted values, NSE accounts for correspondence of values (i.e., the slope and intercept in the relationship). Unlike R^2, NSE can take negative values;

- bias, a measure of the tendency to systematically over or under-predict.

Li (2016) suggested the following narrative for model performance based on NSE[5]:

1. Very poor, NSE < 0.1
2. Poor, 0.1 ≤ NSE < 0.3
3. Average, 0.3 ≤ NSE < 0.5
4. Good, 0.5 ≤ NSE < 0.8
5. Excellent, NSE > 0.8.

5.3.2 Results

Screening for best relationships

The IT screening procedure suggested that no combinations of the available variables produced a regression relationship likely to form a robust predictive model covering all sites. Around 50% of the variance in Chla_92 was explained by a combination of Tmean and DRP (relationship no. 1 in Table 5-3). A plot of residuals did not suggest that polynomial terms of the predictors would improve the model fit. Other main findings, summarised from Table 5-3, follow.

- Tmean was an important predictor in almost all of the relationships identified as “best subsets”, consistent with Tmean being the strongest predictor of Chla_92 as a single variable (36% of the variance in Chla_92 explained by Tmean across all sites).
- When a nutrient variable was included it was generally DRP, rather than DIN.
- Including DRP or NH4N (along with Tmean, a substrate variable and the flow metric Reversals) produced equivalent relationships across sites with flow data. DRP and NH4N were moderately strongly correlated within this dataset (r = 0.67), although not across the entire dataset (r = 0.23).
- DIN featured as a predictor in only two small datasets (no. 16, sites with HS geology; no. 19, full sun sites with a linked flow record, see below).
- The variable DaEF was not a strong predictor of Chla_92 across the 16 flow-sensitive sites (no. 6 and 7). The other variables describing accrual period (Da3, Da7, Da13) were also not strong predictors (no. 11).
- Stronger relationships within the group of flow-sensitive sites were obtained using the flow variables Reversals and Nneg (nos 8, 9, 10) although the relationships’ R^2 were

equation). NSE and R2 are calculated as 1 minus [(sum of squares observed – predicted/ estimated) / (sum of squares observed – mean of observed)].

[5] Li (2016) used a term VEcv (variance explained by cross validation) rather than NSE. The only difference between the two terms appears to be that VEcv is expressed as a percentage rather than a proportion.

only slightly higher than those across all sites with a flow record, using the same predictor variables (e.g., nos 2 and 3).

- Across the five sites identified as flow-insensitive, DRP explained 88% of the variance in Chla_92.
- No strong relationships were identified across the 20 sites with VA geology (nos 13 and 13a). Combinations of variables did not explain more variance in Chla_92 than Tmean alone. However, across the eight sites with VA geology identified as flow-sensitive, pcsand explained 86% of the variance in Chla_92 (negative relationship, no. 14).
- Turbidity and pccoarse explained 75% of the variance in Chla_92 across the nine sites with SS geology (no. 15).
- Tmean and DIN explained 81% of the variance in Chla_92 across the nine sites with HS geology (no. 16). The combination of pcNH4, Tmean and DRP explained 94% of the variance in Chla_92 (no. 16a). However, DRP and pcNH4 were strongly negatively correlated across this group of sites, and VIF in subsequent model runs for both variables was >4. Therefore, the relationship is statistically unstable and was not explored further. Note that pcNH4 and DRP were not strongly correlated across the entire dataset (r = 0.08).
- Relationships across sites classed as full sun (n = 24) were stronger than across those classed as partial shade (n = 14). About 65% of the variance in Chla_92 was explained by a combination of Tmean, turbidity, pcsand and EC across all the full sun sites, with no flow variables and omitting the tidal site (Kerikeri) (no. 17 in Table 5-3).
- Stronger relationships were detected across the smaller datasets of full sun sites at which there was flow data (nos 18 and 19 in Table 5-3). However, the best relationships did not include flow variables and therefore may have been chance correlations (unless sites with flow recorders are characterised by a consistent feature).
- No strong relationships were detected across the 16 Hill sites, or across subsets (no. 23 was the strongest).
- No strong relationships were detected across all Lowland sites. However, Chla_92 at the 10 flow-sensitive sites had strong relationships with one of either DIN, DRP, NH4N or pcNH4 combined with Reversals, Nneg and pccoarse (nos. 25a to 25c). Within this dataset, DIN and pNH4 were strongly correlated (r = -0.87), as were DRP and NH4N (r = 0.86). DIN and DRP were only moderately correlated (r = 0.55). VIF was low in these relationships (<1.5).
- The screening procedure included substituting TN and TP for DIN and DRP. The substitution made little difference to the outcome of the best subsets procedure in terms of variables included at each level and performance of the models (data not shown). Therefore, TN and TP were not considered further in this analysis.

Table 5-3: Summary results of screening for regression relationships between chla_92 and environmental variables. The "best subsets" routine was used to identify promising relationships. The best combinations of predictors were selected using a range of assessment methods (see text). The number of predictor variables was limited to minimise the issue of overfitting models. A common rule of thumb is that, for detection of reasonable sized effects with reasonable power, there should be at least 10 observations for each predictor variable. It is acknowledged that this was usually not achieved. Relationships are referred to in the text using the relationship number (No.) in the right-hand column.

Data set	Flow variables	n	Selected best subset	Adj. R^2	Notes	No.
All sites	None	36 - 39	Tmean, Tmin, DRP	0.481 to 0.542	including or excluding EC and substrate variables gave different R^2 as number of sites changed, but best subset was unchanged	1
All sites with flow data	Reversals, Nneg	21	Tmean, Reversals, DRP	0.643	Including tidal sites	2
	Reversals, Nneg	19	Tmean, Pccoarse, Reversals, DRP	0.810	Omitting tidal sites	3
		19	Tmean, Pccoarse, Reversals, NH4N	0.795	Omitting tidal sites	3a
	Da3, Da7	21	Tmin, Tmean, DRP	0.631	Including tidal sites, accrual variables not in best subsets	4
	Da3, Da7	19	Tmean, Pccoarse, DRP	0.756	Omitting tidal sites, accrual variables not in best subsets	5
Sites partitioned by sensitivity to flow						
Sensitive	DaEF	16	Tmean, Turbidity	0.539	DaEF not included in the best subset	6
		16	Tmean, Turbidity, pH	0.634		6a
		15	Tmean, Turbidity	0.549	Omitting tidal site (Kerikeri)	7
		15	Tmean, Turbidity, pH	0.638		7a
	Reversals, Nneg	16	Tmean, Reversals, Tmin	0.717	Including tidal site	8
		16	Tmean, Reversals, Nneg, DRP	0.781	Including tidal site; addition of DRP improved R^2 (but overfitted?)	9
		15	Tmean, Reversals, Nneg, DRP	0.796	Omitting tidal site (Kerikeri)	10
	Da3, Da7, Da13	16	Tmean, Turbidity, Da3	0.567	Including tidal site	11
Insensitive	None	5	DRP	0.880	Very small dataset!	12
Sites partitioned by REC geology class						
VA	None	20	Tmean	0.230	All sites in VA class	13
		17	Tmean	0.300	Omitting tidal sites and Mangakino (no substrate data)	13a
	DaEF	8	Pcsand	0.856	Negative relationship (chance relationship?)	14
SS	None	9	Turbidity, Pccoarse	0.755		15

Data set	Flow variables	n	Selected best subset	Adj. R^2	Notes	No.
HS	None	9	Tmean, DIN	0.806	Tmean alone had R^2 = 0.501, DIN alone R^2 = 0.416	16
Sites partitioned by shade category						
Full sun sites	None	22	Tmean, Turbidity, Pcsand, EC	0.648	Omitting tidal site (Kerikeri) and Mangakino (no substrate data) (overfitted?)	17
	None	23	Tmean, Pcsand, Turbidity, DRP, pH	0.656	Including tidal site (overfitted?)	20
	All flow vars	12	Tmean, Pccoarse	0.842	Omitting tidal site (Kerikeri)	18
	All flow vars	13	DRP, DIN	0.720	Including tidal site; flow vars not in best subsets	19
Partial shade sites	None	13	Tmean, DRP	0.342	Omitting tidal site (Hatea)	21
	None	14	Tmean, pcsand	0.291	Including tidal site	22
Sites partitioned by upstream slope						
Hill	None	16	Tmean, DRP	0.516	All sites	23
Lowland	None	19	Tmean, EC, Pccoarse	0.373	Omitting tidal sites and Mangakino	24
Lowland, flow-sensitive	Reversals, Nneg	10	DIN, Reversals, Nneg Pccoarse	0.926	Including tidal site (Kerikeri) (overfitted?)	25a
		10	DRP, Reversals, Nneg Pccoarse	0.886	Including tidal site (Kerikeri) (overfitted?)	25b
		10	NH4N, Reversals, Nneg Pccoarse	0.862	Including tidal site (Kerikeri) (overfitted?)	25c

Validation of best relationships

Observed values plotted against values predicted from leave-one-out cross-validation tests always returned lower R^2 than the R^2 of the initial regression relationship. Predictive performance ranged from none (i.e., NSE < 0) to good based on the scale of Li (2016). The main outcomes of the GLM analysis for predicting Chla_92 are summarised below and promising models are summarised in Table 5-4.

- None of the relationships across all sites (either including or excluding the tidally influenced sites, maximum *n* = 39) had predictive skill (i.e., NSE < 0).
- Reducing the dataset to sites with a flow record (*n* = 21) produced relationships with average performance, which improved when the two tidally influenced sites were omitted (model no. 3). Predictors were Tmean, DRP, pccoarse and the flow variable reversals. The similar model (3a) with NH4-N as the nutrient predictor rather than DRP had slightly better performance.
- Reducing the dataset further to include only sites where periphyton was identified as sensitive to flow (maximum *n* = 16), produced relationships with good performance. Predictors were Tmean, DRP, reversals and nneg (models 9 and 10).

- The strong relationship between Chla_92 and DRP at sites where periphyton was identified as insensitive to flow (*n* = 5) had lower cross-validated R^2 than in the original regression. DRP may not be as good a predictor of Chla_92 as initially thought.
- Predictive skill of models across sites with SS and HS geology was <u>good</u>. The model applicable to HS sites included DIN (model 16), but the one for SS sites did not include DIN or DRP.
- Full sun sites had stronger relationships than partial shade sites, but all relationships for the former performed <u>poorly or very poorly</u> when cross-validated (NSE < 0.3).
- Predictive skill for lowland, flow-sensitive sites was <u>excellent</u> when DIN was a predictor, and <u>good</u> when DRP was a predictor. An additional model including NH4N as an alternative nutrient predictor also had good performance, although NH4N was strongly correlated with DRP (71% variance explained).

The GLM procedure also generated relationships for maximum annual chlorophyll *a* for individual years. With few exceptions, these relationships had lower predictive skill than those developed for Chla_92 (i.e., using the entire dataset). For that reason, the annual relationships were not considered further.

Note that the last three models (25a, b and c) apply to a subset of the sites in models 9 and 10. They were included as a double check on the performance of models 9 and 10, but also provide a model including DIN as a predictor rather than DRP.

Table 5-4: Model details for relationships assessed as potentially useful for predicting Chla_92 across Northland rivers. Model No. in column 2 is the reference number for the relationship from Table 5-3. The main criterion for the assessment was model performance of at least good (i.e., NSE > 0.5), using the scale suggested by Li (2016). Note that some of the regression relationships that had strong explanatory power across the initial dataset (e.g., > 80% of variance in Chla_92 explained) had relatively weak predictive performance as indicated by NSE. An example below is relationship 3 (shaded). For relationship 12, the cross-validated adjusted R^2 for the strong relationship between Chla_92 and DRP across five sites was only 0.57 (0.3 lower than the adjusted R^2 of the original relationship). NA, NSE could not be calculated because the dataset was too small. Under relationship statistics, SS-resid is the sum of squares of the residuals, used to calculate uncertainties in predictions.

	Model No.	N sites	Variables and coefficients											Relationship statistics		Cross-validation	
Dataset			Intercept	Tmean	Turbidity	DRP	DIN	NH4N	pcNH4	Reversals	Nneg	Pccoarse	Pcsand	SS-resid	Adj. R^2	Adj. R^2	NSE
All sites with a flow record, with reversals and nneg as potential flow predictors	3	19	-3.948	0.378		0.488				-0.007		0.005		0.59	0.81	0.66	0.50
	3a	19	-3.507	0.401				0.726		-0.011			-0.126	0.63	0.80	0.67	0.56
Flow-sensitive sites, including flow variables (but not DaEF), all sites	9	16	0.873	0.326		0.289				-0.010	-0.013			0.21	0.78	0.72	0.70
Flow-sensitive sites, including flow variables (but not DaEF), excl. tidal site	10	15	0.365	0.339		0.286				-0.009	-0.012			0.19	0.80	0.74	0.72
Flow insensitive sites	12	5	-0.987			2.008								0.248	0.88	0.57	NA
All sites with SS geology, no flow variables	15	9	0.983		0.321							0.011		0.34	0.75	0.64	0.51
All sites with HS geology, no flow variables	16	9	-3.43	0.279			0.326							0.166	0.81	0.73	0.68
Lowland, flow-sensitive sites	25a	10	6.061				0.174			-0.0165	-0.0106	0.0048		0.03	0.96	0.84	0.82
	25b	10	5.773			0.180				-0.014	-0.010	0.006		0.048	0.87	0.77	0.76
	25c	10	6.071					0.177		-0.014	-0.011	0.0055		0.059	0.86	0.75	0.68

5.4 Discussion

5.4.1 Comment on model performance

The only relationships assessed as good or excellent (Table 5-4) were derived from small datasets. These models therefore run the risk of being overfitted, even though they performed well in cross-validation. The implication is that they may perform poorly when applied to new sites, even when those sites conform to the site type that defined the original dataset.

5.4.2 Drivers of periphyton in Northland rivers

The above analysis cannot provide a definitive answer to NRC's main question (*What are the major drivers of periphyton growth in Northland?*) because the results are based on correlations only. However, a reasonable assumption, based on earlier research (see Section 4.1), is that the predictors selected in the analysis represent processes that do affect periphyton growth, biomass accumulation, and biomass removal in rivers. Therefore, we assume that the relationships at least partly represent cause and effect.

Based on the results in Table 5-4, factors that may influence peak periphyton biomass in Northland rivers are discussed below.

Mean water temperature

Tmean was more strongly correlated with Chla_92 than any other variable (r = 0.61; the next strongest correlation was with TN, r = 0.39). Water temperature is expected to influence periphyton biomass through promoting more rapid algal growth rates (DeNicola 1996). In streamside channel experiments, periphyton biomass increased when water temperature was artificially raised by just 1.4 °C (Piggot et al. 2011). Water temperature is clearly strongly influenced by season, but the mean temperature at a site is also expected to be related to degree of shading, and altitude. The range of Tmean across the 39 periphyton monitoring sites in Northland was 13.8 to 16.9 °C.

Temperature observations were monthly spot measurements, which are subject to bias because river water temperatures always fluctuate diurnally. If spot temperatures are consistently taken at the same time of day, then Tmean could reflect the time of collection rather than a characteristic mean for the site that can be compared to that at other sites.

The raw data provided by NRC included the time of each observation. A preliminary analysis of the data showed that the mean observation time (from 2015 to 2018) ranged from 09:20 h to 13:20 h, with a range of times covered at all sites. Mean observation time explained 15% of the variance in Tmean with a positive correlation.[6] However, catchment altitude (extracted from the database linked to the REC) explained 21% of the variance in Tmean (negative correlation). Omitting data from 14 sites at which the mean observation time was later than 11:20 h, altitude explained 66% of the variance in Tmean. Furthermore, average Tmean at full sun sites (16.2 °C) was significantly higher than average Tmean at partially shaded sites (15.2 °C) (two sample T-test, $P < 0.001$).

[6] The time of data of temperature observations may have led to two sites (Hakaru at Topuni and Peria at Honeymoon Valley) appearing as outliers in the relationship shown in Figure 5.4, with much higher Chla_92 than expected from their mean temperature. The preliminary analysis of observation times showed that both sites were typically sampled early in the day (before 10:15 h on average). Minimum water temperatures in rivers occur just after dawn, and maximum temperatures occur in mid- to late-afternoon (depending on the time of year and weather conditions). As an example, daily temperature amplitude in a Canterbury river in mid-summer was typically 4.3 °C, and the difference between temperature at 10:15 h and 13:00 h was ~2 °C.
Other Northland sites typically sampled between 09:20 h and 10:30 h (on average) had lower Chla_92 (presumably driven by other factors) and were not outliers in the relationship. In addition, some of these sites were shaded or partially shaded.

We concluded that the temperature data provided by NRC likely represented a characteristic mean temperature at many sites, but the range of observation times introduced some "noise" into the dataset. Continuous temperature loggers (e.g., 15 minute to hourly logged observations) will provide more accurate data. It is important to locate loggers so that they record unbiased temperature in flowing water but are safe from the effects of flood events. The range of Tmean in Northland overlapped that of the Horizons and Canterbury datasets (Appendix D) but median Tmean (16.1 °C) was 3.5 °C and 4.3 °C higher than the medians in the Horizons and Canterbury datasets respectively. Such differences are large in terms of effects on periphyton growth (DeNicola 1996).

DRP

In contrast to patterns seen in other regions, DRP emerged as the primary nutrient correlate with Chla_92 in the Northland sites. For example, in the Horizons region, DIN was included in almost all strong between-site relationships (with a positive effect) and alone explained a significant proportion of variance in Chla_92 across sites; on the other hand, DRP was only weakly correlated with Chla_92 and rarely featured as a predictor (Kilroy et al. 2018). A similar pattern of DIN as the dominant nutrient predictor variable was found across sites in Canterbury (Kilroy et al. 2017).

Dominance of DRP or DIN as predictors of Chla_92 could be interpreted as, respectively, general DRP or DIN limitation of periphyton biomass across a region. However, regional data (summarised in Appendix D) do not suggest general P-limitation in Northland and N-limitation in the Horizons and Canterbury regions. For example, in Northland, DIN : DRP ratios[7] based on the data in Appendix B suggest that periphyton growth may be N-limited at 21 Northland sites, P-limited at 13 sites and co-limited at the remining five sites. Average statistics from the dataset (Appendix D) confirm that mean and median DIN in the Northland dataset are low compared to that in the Horizons and Canterbury Regional Council datasets, while mean and median DRP are similar to that in the Horizons region, but much higher than in Canterbury. All, these patterns suggest predominant N-limitation in Northland rivers, which contradicts the finding that Chla_92 was generally more strongly correlated with DRP than with DIN across the Northland dataset.

Across 10 lowland sites identified as flow-sensitive, inclusion of either DIN or DRP or NH4N all yielded good predictive relationships. The three nutrient variables were intercorrelated ($r > 0.55$), but none was strongly correlated with Chla-92. Both DIN and DRP spanned a wide range (respectively 16 – 1077 and 5 – 92 mg/m^3), and the lower concentrations of both were likely to be below those that saturate periphyton biomass (e.g., DRP ~ 28 mg/m^3, Bothwell 1989; DIN ~ 300 mg/m^3, Dodds 2002, 2006). Nevertheless, highest Chla-92 occurred at Waiharakeke at Stringers Road, where both DIN and DRP were below those thresholds. The role of individual nutrients at these sites cannot be determined without further investigations such as nutrient diffusing substrate assays (e.g., Francouer et al. 1999).

The scope of the present analysis did not include any analysis of seasonality of chlorophyll *a* or nutrient concentrations and ratios. Such analysis may be necessary to understand the role of DIN and DRP concentrations in periphyton growth at individual sites in relation to other features of the site. Northland Rivers include some that show strong seasonal fluctuations in DIN in particular.

[7] When N or P are in short supply, periphyton growth is, respectively, N- or P-limited. The classical theory of nutrient limitation of the growth of plants and algae holds that plant growth is N-limited when the ratio of available N to available P is less than 7 to 1 (by weight, equivalent to a molar ratio of 16 to 1), and P-limited when the N to P ratio is greater than 7 to 1 (by weight). The ratio originated from work on marine algal cells, which were found to contain N and P in a more or less consistent molar ratio of 16 to 1 (Redfield 1958). Thresholds for determining nutrient limitation in New Zealand river are typically: N-limitation, DIN/DRP <7; P-limitation, DIN/DRP >15; co-limitation, DIN/DRP 7 – 15 (e.g., McDowell et al. 2009).

It is also important to appreciate that water column concentrations do not always reflect availability of nutrients but are used as a convenient surrogate for nutrient availability[8]. Therefore, unexplained correlations are to be expected, and indicate that we should not assume that the regression equations represent simple cause and effect, even if the predictors are consistent with our general understanding of drivers of periphyton growth.

DIN

In contrast to the general pattern of correlation between Chla_92 and DRP, DIN was a strong predictor of Chla_92 across the nine sites with HS geology, when combined with Tmean. Based on ratios, N-limitation was suggested at two sites, P-limitation at four sites and co-limitation at the remaining three. Again, some site-specific analysis could assist with understanding responses to DIN and other factors at HS sites.

As noted above, DIN concentrations were relatively low at many of the Northland sites (e.g., median annual mean DIN of 88.9 mg/m3. Appendix C). Therefore, it was surprising that DIN did not emerge as a more significant correlate with Chl-92. .

Ammoniacal N

NH_4-N is theoretically the most energy-efficient source of N for algae and preferential uptake of reduced (e.g., N as the NH_4^+ ion) versus oxidised (e.g., N as NO_3^-) forms of N in aquatic primary producers has been studied for decades (see review by Syrett 1981). Nevertheless, the implications for freshwater ecosystems of changes in the composition of N supplies to primary producers are complex (e.g., Glibert et al. 2016). A recent review found few published studies focussed on responses by stream periphyton to changes in NH_4-N concentrations or proportions (Kilroy 2016, but see Kilroy et al. 2018b).

In the present Northland dataset, concentrations and proportions (as a % of DIN) of NH_4-N were higher than is typical in many New Zealand rivers. Across all 77 sites in the National Water Quality Monitoring Network (NRWQN), mean and median NH_4-N concentrations were 10.4 and 4.9 mg/m^3, respectively, with median values at individual sites ranging from 1.0 to 72 mg/m^3 (data from 2011 – 2015) (Kilroy 2016). Equivalent values from the 39 Northland sites were 16.6 and 9.0 mg/m^3, ranging from 3.4 to 71 mg/m^3 (data from 2015 – 2018). Mean and median NH_4-N as a percentage of DIN in the NRWQN (i.e., pcNH4) were respectively 3.7% and 3.2%. Equivalent values from the 39 Northland sites were 19% and 8%.

The pattern of high pcNH4 in Northland may arise from low DIN concentrations in some rivers: rivers with low DIN tend to have the highest proportions of NH_4-N, presumably due to natural processes (Kilroy 2016). Under natural conditions, sources of NH_4-N in streams include rainfall (Timperley et al., 1985), seepage from catchments (McClain et al., 1994, Peterson et al., 2001, Wetzel 2002), instream bacterial reduction of NO_3-N, remineralisation of organic N such as decaying algae (reviewed by Wetzel 2002), and release from live algae as means of releasing excess nutrients during photo-inhibition (Lomas et al., 2000). Collos and Harrison (2014) suggested that NH_4-N concentrations derived from natural sources in surface waters typically range up to 42 mg/m^3. Based on geometric mean values (2015 – 18) NH_4-N at only two Northland sites exceeded this threshold (Waiaruhe

[8] Algae typically obtain nutrients from the surrounding medium and respond to increased nutrient supply with increased growth rates (up to the point of saturation). The "surrounding medium" is usually the overlying water but can include the periphyton mat itself when nutrients are released from organic compounds during chemical (redox) processes. Furthermore, during long periods of accrual, periphyton may be taking up nutrients as fast as they are being supplied from upstream so that concentrations become decoupled from availability (and therefore accrual).

downstream Mangamutu Confluence, 71 mg/m^3; Ruakaka at Flyger Road, 44 mg/m^3). Furthermore, NO_x-N was strongly and negatively correlated with pcNH4 (86% of the variance in pcNH4 explained by NO_x-N). Waiaruhe downstream Mangamutu Confluence was statistically identified as an outlier in that relationship, with higher pcNH4 than expected from the relationship across other sites (Figure 5-5).

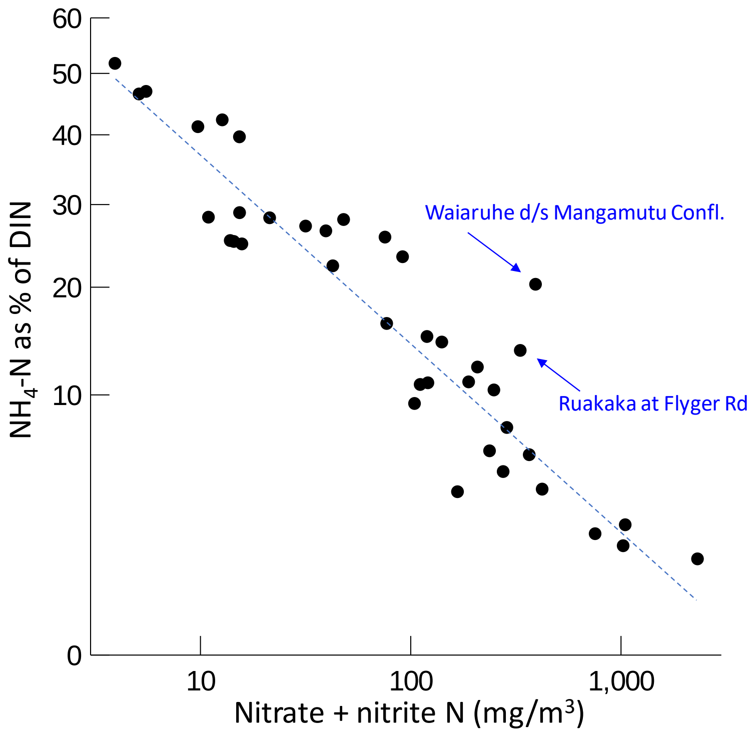

Figure 5-5: Percentage of NH_4-N in DIN (pcNH4) plotted against NO_x-N showing a strong negative relationship. Values are means over the period 2015 – 18 (geometric mean for NO_x-N). The two sites with highest NH_4-N concentrations (Waiaruhe d/s Mangamutu confluence, Ruakaka at Flyger Rd) are highlighted with blue arrows. Excluding these two sites, NO_x-N explained 91% of the variance in $pcNH_4$. Note that Waiaruhe was identified in the regression an outlier in the relationship.

From the above, relatively high proportions of NH_4-N in DIN at many Northland Rivers may represent natural concentrations at many sites. More detailed knowledge of the sites and of potential upstream sources of NH_4-N (both natural and anthropogenic) is needed to establish potential sources.

In relation to developing empirical models for predicting periphyton chlorophyll *a*, the strong correlations between DIN or NO_x-N and NH_4-N or pcNH4 mean that it was not possible to isolate any effect of NH_4-N on Chla-92 from the effect of DIN in general using regression methods. NH_4-N has been shown experimentally to lead to higher chlorophyll *a* in periphyton than the equivalent concentration of NO_3-N (Kilroy et al. 2018b). However, both the concentration of NH_4-N and its proportion of DIN in the experimental treatment showing a significant effect were much higher than any encountered at the Northland sites (i.e., 390 mg/m^3 NH_4-N making up 77% of DIN compared with maxima of 71 mg/m^3 and 52%, respectively, at the Northland sites). In the experiment, a lower concentration (160 mg/m^3 NH_4-N making up 30% of DIN) showed only a marginally significant effect compared with background conditions (2.2 mg/m^3 NH_4-N making up 0.5% of DIN).

Overall, at this stage there is no evidence to suggest that the higher-than-typical (for New Zealand) concentrations and proportions of NH_4-N in Northland rivers have a significant influence on Chla-92. Two models were identified in which NH4N was a predictor (3a and 25c in Table 5-4). These models were not investigated further because 3a had relatively weak predictive skill and 25c applied to a small dataset in which DRP and NH4N were highly correlated. As suggested above for DIN and DRP, site-specific analysis of NH_4-N over time (i.e., using monthly data) may highlight patterns not evident from three-year means.

Flow variables

Accrual period either based on a uniform flow magnitude (e.g., 3 x median flow) or on the empirically determined effective flow (EF, see Section 4) did not appear as a predictor in any of the relationships in Table 5-4. This was unexpected. The variable Da3 was the basis of the strong periphyton – nutrient relationships developed by Biggs (2000b). The variable DaEF has proved to be key to obtaining robust periphyton – environment relationships in the Horizons region (Kilroy et al. 2018). The variable DaEF was also helpful for improving relationships across the dataset from Canterbury (Kilroy et al. 2017).

Although DaEF was not identified as a strong predictor of Chla_92 in Northland, identifying flow-sensitive sites (Section 4) and distinguishing them from flow-insensitive sites was useful because we identified better predictive relationships across the flow-sensitive sites than across all the sites with a flow record. Two flow variables were included in the relationships with negative coefficients: reversals and nneg (see Table 5-1, Table 5-4).

Reversals is a count (averaged per year) of the number of times flow switches from declining to increasing and vice-versa. A higher reversals count indicates more variable flow but provide no information on the magnitude of the reversal. A negative relationship is expected between reversals and periphyton biomass because more variable flow is associated with more frequent removal of biomass.

Nneg is the number of days per year when the flow is lower than that on the preceding day. Increasing nneg indicates increasing “flashiness” of the flow regime. Nneg is expected to show some congruity within a region in the same time period because all sites will be affected by the same general weather patterns. Within a region, higher nneg indicates that floods rise more rapidly and fall more gradually. A negative relationship with periphyton would be expected because rapidly increasing flow promotes periphyton biomass removal (Biggs and Thomsen 1995).

Both reversals and nneg have been shown to be useful predictors in previous periphyton regression relationships (Snelder et al. 2014). Both are readily computed from a record of daily mean flows.

Turbidity and substrate

Turbidity and pccoarse combined showed borderline “good” performance for predicting Chla_92 across sites with SS geology (Table 5-4). Despite not including a nutrient variable, the relationship was included to illustrate that other variables can be as important as nutrients. Both variables had a positive coefficient. A positive relationship with Chl_92 is expected for pccoarse because large stable substrates provide attachments for algae that resist removal by high flows. The positive coefficient for turbidity was counter-intuitive because the general effect of high turbidity on periphyton is to reduce or limit growth as a result of reduced light availability and potential for smothering when fine sediment settles out of the water column (Wagenhoff et al. 2011). A plot of the raw data (Chla_92 vs. turbidity) indicated that a first-order polynomial relationship fits the data better than a linear relationship. In other words, the relationship is hump-shaped, with a negative relationship only when concentrations are in the high range (data not shown). This makes sense because low to moderate fine sediment (i.e., turbidity) may have a positive effect on some types of periphyton (Wagenhoff et al. 2013).

Effect of geology

Responses by periphyton to environmental variables appeared to vary with the dominant geology of the upstream catchment, as summarised by the REC geology classification. To explore this further, we used box plots to compare a range of variables, including Chla_92, across the three geology classes. The plots (Figure 5-6) showed variability within each geology class so that differences in mean values among the classes were not statistically significantly different in many cases (i.e., ANOVA, $P > 0.05$). However, some patterns were evident:

- DRP (and also TP, not shown) tended to be higher in SS sites than VA sites ($P > 0.1$), but there was no difference between classes in DIN (or TN);
-
- EC tended to be lower at VA sites than at SS sites ($P = 0.1$) and turbidity was higher at SS sites than at VA sites ($P < 0.05$).
- Pcsand was lower at VA sites than at either HS or SS sites ($P < 0.07$)
- There were differences in flow metrics between the geology classes (but note smaller numbers of sites with flow data: HS, 5; SS, 5; VA, 11 sites). Flow differences are likely attributable to catchment location and climate rather than geology but may contribute to the differences in periphyton – environment relationships among classes.
- Mean Chla_92 tended to be higher in SS sites than VA sites ($P < 0.08$).

The above interpretation of Figure 5-6 suggests that geology-associated differences in environmental characteristics may drive variability in periphyton – environment relationships in the three REC geology classes. From a practical perspective, geology-associated effects could imply that different nutrient limits might apply to different geological classes.

Lack of relationship with EC

The analysis of the Northland dataset contrasted with those for the Canterbury and Horizons datasets in that EC was rarely included as a predictor of Chla_92 (Section 5.3.2, Table 5-3).

In Canterbury, EC combined with DIN and DaEF explained a high proportion of the variance in Chla_92 across unshaded sites with hill-fed flows. EC was also included in other relationships developed using annuals datasets (Kilroy et al. 2017). In the Horizons region, EC was the most important predictor of Chla_92 in the many relationships tested, followed by DIN and DaEF (Kilroy et al. 2018). The role of EC in influencing Chla-92 was discussed in those reports but is still unclear.

Excluding the two tidally influenced sites (Hatea at Mair Park and Kerikeri at Stone Store) EC in Northland covered a similar range to that in the Canterbury and Horizons regions (see Appendix C). Therefore, the lack of relationships with Chla_92 cannot be explained by different ranges of values. We speculate that it is possible that higher water temperatures in Northland rivers (see Section 5.4.2) influence periphyton biomass strongly enough to override effects in cooler regions. Further investigation (e.g., a literature review) is required to understand this difference between regions.

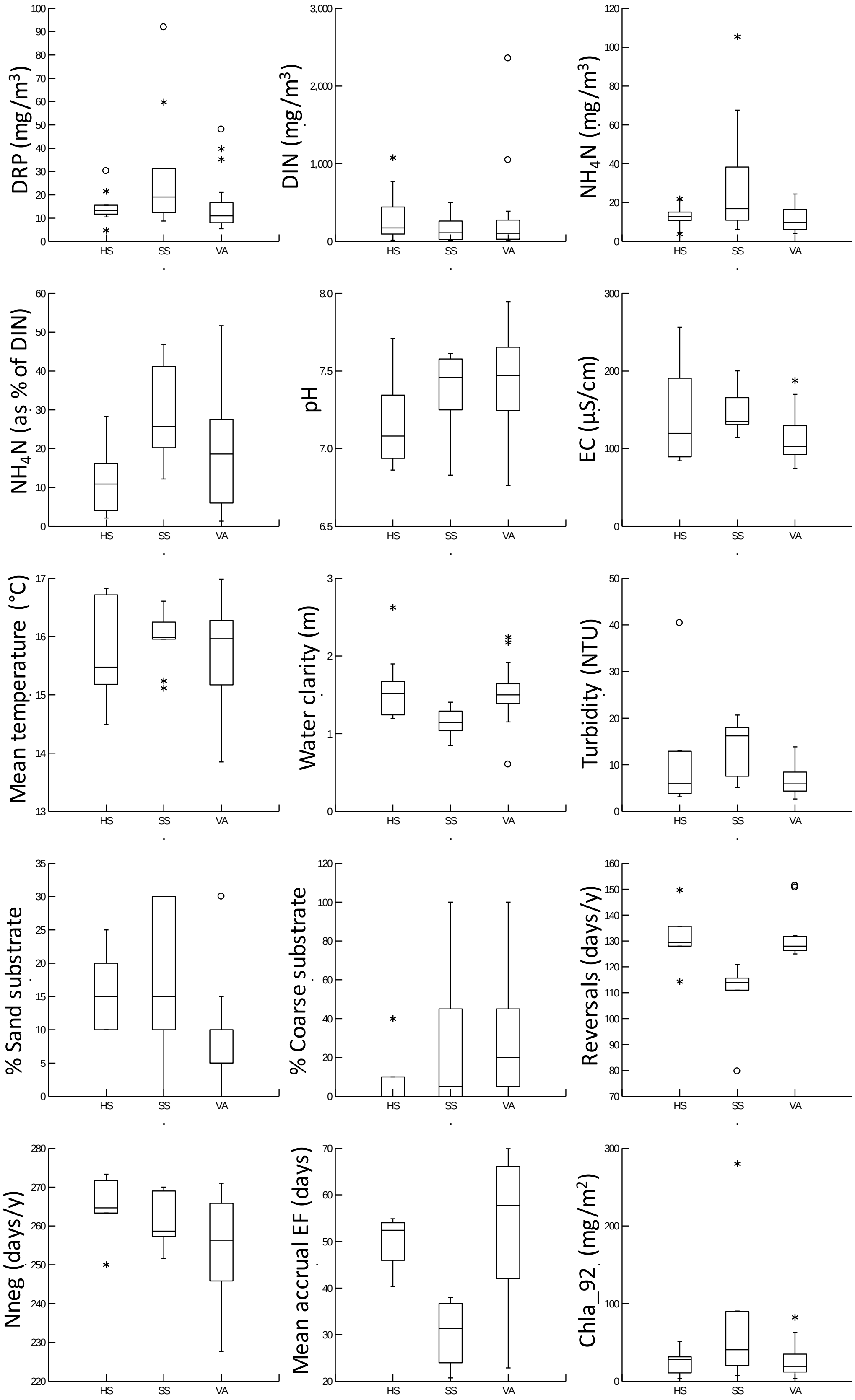

Figure 5-6: Box plots showing medians and ranges of environmental variables at sites in REC geology classes HS, SS and VA. Mean values of each variable. The line inside each box shows the median value; the box shows the range of the central 50% of all values, the whiskers show the values that fall within 1.5 times the range of the box. Asterisks and circles are outliers.

6 Development of nutrient criteria for Northland rivers

6.1 Approach

The simplest method for deriving nutrient criteria based on regression relationships with one or more predictors (i.e., those listed in Table 5-4) comprises the following steps.

1. Specify values for each of the predictors included in the selected regression relationship. For example, in Model No. 9 in Table 5-3, Chla_92 could be predicted for all combinations of Tmean = 15, 16 and 17 °C, reversals = 10, 30 and 50 per year, nneg = 245, 260 and 275 days / year, and DRP concentrations from 4 to 90 mg/m^3 (i.e., 27 different combinations of Tmean, Reversal and nneg at each concentration of DRP).

2. Use the relationship coefficients to calculate predictions (of Chla_92 in this case) for all combinations of values of the non-nutrient predictor variables along the gradient of DIN or DRP.

3. Back-transform predictions of Chla_92 including an adjustment to correct for asymmetric confidence intervals around the mean when back-transformed (Dambolena et al. 2010).

4. Specify uncertainty around the predictions as the 95% confidence interval.[9]

5. Plot the predictions as a set of curves on an x – y plot, where x = DIN or DRP, and y = Chla_92.

6. Use the curves to read off the DRP or DIN concentration that corresponds to target Chla_92 for the site of interest. Capture uncertainty by reading DRP and DIN for the upper and lower confidence limits around the target Chla_92.

7. For highest confidence that the target will achieve the required Chla_92 (given other specified environmental conditions) the DRP / DIN concentration corresponding to the upper limit of the 95% confidence interval (UCL) would be taken as the limit.

The method was applied to Model Nos 9, 12, 16, 25a and 25b in Table 5-4. We used three values for each predictor other than the nutrient variable. Predictor values were selected based on data from the sites used to develop each model, to represent the lower, middle and upper parts of the range.

6.2 Results

DRP and DIN limits (as the estimate and UCL) corresponding to Chla_92 of 50, 120 and 200 mg/m^2 under selected combinations of values of each predictor are summarised in Table 6-1. Provisional lookup plots are in Appendix D. The plots were derived from spreadsheet calculations which can be provided if required. Nutrient limits could not be determined in many cases because the predictions would have been beyond the range of the dataset used to derive the model.

[9] We calculated the back-transformed 95% CI around each estimate using the modified Cox method for calculating CI for the mean of a log-normal distribution as (Olsson 2005):

$$10 \wedge \text{Estimate} + S^2/2 \pm 2.2 \sqrt{[(S^2/n) + (S^2 * S^2)/2(n-1)]}$$

where S^2 is the mean squared error of the model, and n is the number of samples used to derive the model.

Table 6-1: Summary of DRP and DIN concentrations corresponding to the Chla_92 thresholds separating the NPS-FM bands under a set of specified values for each predictor. The concentrations can be regarded as empirically derived criteria that apply to the groups of sites used to derive the relationships. The values were read off the plots in Appendix D, for selected combinations of predictor variable values. DRP limits shown first, then DIN.

A criterion of >90 (for DRP) and >1000 (for DIN) indicates intersection of the predictions and the threshold somewhere beyond the upper limit of the nutrient range. NA means that a concentration could not be determined because the predictions did not intersect the Chla_92 threshold at all. In these cases, it is assumed that other factors are limiting periphyton, and any limits set would need to take downstream effects into account.

Model (from Table 5-4) and dataset	Nutrient	Predictors and selected values				DRP or DIN (mg/m^3) associated with Chla_92 less than:					
		Tmean	Reversals	Nneg	Pc-coarse	Estimate			Upper confidence limit		
		°C	n/y	Days/y	%	50	120	200	50	120	200
		16	110	245		NA	7	50	NA	5	28
Model 9. **Flow sensitive sites**	**DRP**	16	110	260		<4	39	NA	NA	24	NA
		16	130	260		9.5	NA	NA	6	>90	NA
			120	245	20	<4	50	NA	<4	22	NA
Model 25b. **Flow sensitive, Lowland sites**	**DRP**		120	260	20	<4	NA	NA	NA	>90	NA
			120	275	20	17	NA	NA	10	NA	NA
Model 12. **Flow-insensitive sites**	**DRP**					21	34	43	15	24	30
			120	245	20	<10	740	NA	<10	410	>1000
Model 25a. **Flow sensitive, Lowland sites**	**DIN**		120	260	20	40	NA	NA	25	>1000	NA
			120	275	20	360	NA	NA	185	NA	NA
		15				720	NA	NA	350	NA	NA
Model 16. **Sites with HS geology**	**DIN**	16				100	>1000	NA	50	720	NA
		17				15	200	980	<10	100	510

6.3 Limitations of the method

In theory, this method is simple and allows derivation of site-specific targets across a region. The targets can be averaged (for example) to obtain a more generalised nutrient target.

In practice, the following cautions apply:

- The predictions are reliable (within the range of uncertainty defined by the 95% confidence interval) *only when used with data that falls within the range of the data used to develop the relationship*.

- The above applies to combinations of data. For example, reversals were never > 130 when nneg was > 250.
- The current models only apply to certain types of sites (e.g., flow sensitive, HS geology) and cannot be used at the other sites.
- When using the models, we need to take account of what actually occurs at sites. If a site already consistently meets periphyton targets, then there would be no justification for setting nutrient criteria lower than those currently observed. The reverse also applies.

The above means that at this stage, nutrient targets cannot be suggested for all Northland sites based on the analysis in this project. Recommendations for steps that might enable the scope to be widened are provided in Section 7.

The nature of the relationships also means that nutrient criteria may need to be site- or river-specific, because the predictions take account of other site conditions (i.e., flow variability, water temperature) as well as nutrients. The spreadsheets developed during the analysis, combined with the site information in Appendix A can be used to derive site-specific nutrient criteria.

We reiterate here the comment in Section 5.4.1 that the relationships used to derive the nutrient criteria in Table 6-1 were derived from small datasets. Even though the models performed well in cross-validation, there is no guarantee that they will perform well when tested on new sites, even when those sites conform to the site type that defined the original dataset. Expanding the datasets available for model development may be helpful.

7 Review of Northland's periphyton monitoring programme

The final question asked by NRC was:

> *"Is Northland's current periphyton monitoring programme fit for purpose, in relation to (a) setting numeric freshwater periphyton objectives for Northland's rivers, and (b) monitoring progress towards the achievement of the freshwater objectives in the context of the NPS-FM?"*

In the following, we address (b) first followed by (a), because (b) is the primary purpose of the programme. All recommendations are summarised in Section 8 (Synthesis and recommendations).

7.1 Monitoring progress towards NPS-FM freshwater objectives

We assume that "NPS-FM freshwater objectives" refer only to the periphyton attribute of the NPS-FM and not to other attributes (e.g., NO_3-N, NH_4-N toxicity attributes). The NPS-FM (NZ Government 2017) includes the following requirements relevant to NRC's question, which are addressed below in turn:

1. the requirement to set periphyton objectives for freshwater management units (FMUs) in terms of the bands defined in the NPS-FM periphyton attribute (Objective CA1; policy CA2(d) in the NPS-FM);

2. the requirement to provide for an approach to the monitoring of progress towards, and the achievement of freshwater objectives (Objective CB1; policy CB1 in the NPS-FM);

For requirement 1, the state of the environment monitoring sites included in the periphyton monitoring programme are assumed to have been selected to represent FMUs. An analysis of sites in relation to their representativeness within the region was considered to be outside the scope of this study and may already have been completed. Nevertheless, the assignment of sites to REC classes indicated good representation in three geology classes (see Table 5-2). Most sites (72%) were in the pastoral (P) landcover class, 15% had catchments in indigenous forest (IF) and the remaining sites had exotic forest (EF) or urban (U) catchments. All sites were in the Warm Wet (WW) climate category and all by one site were classed as Lowland in REC (one site was lake-fed (Lk, Watercress at SH1).

The periphyton attribute requires monthly monitoring to enable assignment of current state to each site, using at least three years of monitoring data. This was achievable as of December 2017 for 36 sites. Three sites added to the programme in mid-2016 (Pukenui, Punaruku, Tapapa) were provisionally assessed as falling into band A based on less than 24 months of data. These sites can be fully assessed in mid-2019 when 36 months of data will be available.

We assume that sample collection methods (i.e., sample collection for the determination of chlorophyll *a*) follow recommended procedures such as those set out in Biggs and Kilroy (2000). Sample collection for chlorophyll *a* is subject to considerable variability (Kilroy et al. 2013), but the recommended methods (Biggs and Kilroy 2000) at least provide enough precision to assess sites relative to thresholds (Kilroy et al. 2013).

Laboratory analyses of samples collected by NRC have been carried out at NIWA in Christchurch since about 2013. We follow the hot ethanol extraction method followed by spectrophotometric reading of chlorophyll *a* concentration with an acidification step to correct for degradation products (phaeophytins), as recommended by and described in Biggs and Kilroy (2000). Therefore, there has been consistency over time in treatment of the samples. There is also consistency with other regions. For example, all chlorophyll *a* sample analyses for the three-year Canterbury periphyton dataset, and for the ongoing Greater Wellington periphyton programme, were carried out at NIWA, Christchurch, using the same methods. Samples in the Horizons programme are analysed at a different laboratory but using the same method. An inter-laboratory comparison identified some discrepancies between analyses on the same samples (Kilroy et al. 2012). The main difference was a bias towards higher values in one laboratory compared to the other. The differences were relatively small.

In this report we assessed the effect of missing periphyton data (through, for example, high river flows) on grading against the NPS-FM periphyton attribute. We found that gradings made using two different methods were the same at all sites but one. Therefore, missing data is not a major issue in Northland.

Overall, the size of the monitoring programme (number of sites) is good compared to the size of the region (one site per 320 km^2, on average, compared to, for example, one site per 364 km^2 in the Horizons region). Sample collection methods have not been reviewed in detail, but our understanding is that they follow standard procedures. Sample analysis methods (for chlorophyll *a*) are consistent with those used by at least three other regions.

7.2 Monitoring related to setting numeric objectives for Northland's rivers

It is assumed that "setting numeric objectives" refers to the further requirement in the NPS-FM for councils to set appropriate exceedance criteria for DIN and DRP for achieving the periphyton objectives within and FMU, as directed in the note following the periphyton attribute table in the NPS-FM.[10]

The MfE periphyton note guidance document suggested a process that regional councils could follow, summarised in Figure 2 of MfE (2018). The important steps in that process relevant to this review are:

- Site selection: 2. Select suitable periphyton monitoring sites
- Data collection: 3. Monitor periphyton
- Data collection: 4. Collect data on controlling factors

7.2.1 Site selection: 2. Select suitable periphyton monitoring sites

A requirement for deriving reliable ecology (i.e., periphyton) vs. environment models is as large a dataset as possible, covering the entire range of interest of all variables of interest. In view of the importance of nutrients and flow metrics as predictors, Kilroy et al. (2008) suggested that initial site selection could be based on a matrix of three levels of flow variability (represented by FRE3, the mean annual frequency of events greater than three times median flow) versus three levels of nutrient enrichment.

[10] The wording in the NPS-FM periphyton attribute Note is: *"To achieve a freshwater objective for periphyton within a freshwater management unit, regional councils must at least set appropriate instream concentrations and exceedance criteria for dissolved inorganic nitrogen (DIN) and dissolved reactive phosphorus (DRP). Where there are nutrient sensitive downstream receiving environments, criteria for nitrogen and phosphorus will also need to be set to achieve the outcomes sought for those environments."*

Applying the method to the existing Northland dataset showed reasonable coverage of the 21 sites with a flow record across the nine possible combinations, though with some bias towards sites with medium flow variability and medium enrichment (Table 7-1).

Table 7-1: Assessment of sites in the Northland periphyton dataset for representativeness for development of periphyton – nutrient relationships. Nutrient enrichment categories were defined as LOW = (DIN + (DRP * 10)) < 200 and DIN < 100; HIGH = (DIN + (DRP * 10)) > 400 and DIN > 300. MEDIUM was anything in between. DIN and DRP in mg/m^3 (geometric means from Appendix A). Flow variability categories were: LOW, FRE3 < 11; MEDIUM, FRE3 11 – 14; HIGH, FRE3 ≥ 14. *Kaihu at Gorge was borderline between low and medium enrichment. Sites are colour coded according to their NPS-FM grading (see Table3-5). The NPS-FM gradings do not affect the representativeness exercise but provide an idea of periphyton patterns in relation to the enrichment and flow variability gradients.

Flow variability	Nutrient enrichment		
	LOW	MEDIUM	HIGH
LOW		Kaihu at Gorge*	Ruakaka at Flyger Road
		Waitangi at SH10	Otaika at Otaika Valley Road
		Waiharakeke at Stringers Rd	Waipao at Draffin Road
		Mangahahuru at Main Road	
MEDIUM	Waipoua at SH12	Ngunguru at Coalhill Lane	Hatea at Mair Park
	Mangakahia at Twin Bridges	Waitangi at Waimate North Rd	Hakaru at Topuni
	Opouteke at Suspension Br	Punakitere at Taheke	Raumanga at Bernard Street
HIGH	Waipapa at Forest Ranger	Awanui at FNDC	Kerikeri at Stone Store
		Victoria at Victoria Valley Road	
		Waiarohia at Second Avenue	
NO FLOW DATA	Waimamaku at SH12	Waipapa at Waimate North Rd	Waiaruhe d/s Mangamutu Confl.
	Kaeo at Dip Road	Waiaruhe at Puketona	Peria at Honeymoon Valley Rd
	Punaruku at Russell Road	Waipapa at Landing	Waiarohia at Whau Valley
	Oruaiti at Sawyer Road	Pukenui at Kanehiana Drive	Watercress at SH1
	Oruaiti at Windust Road	Mangakino at Mangakino Lane	
	Stony Creek at Sawyer Road	Mangamuka at Iwitaua Road	
		Pekapeka at Ohaeawai	
		Tapapa at SH1	

The only "empty" combination was low flow variability and low nutrient enrichment, but we noted that Kaihu at Gorge was borderline between low and medium nutrient enrichment status. The dataset would benefit from addition of more sites with low nutrient enrichment (as defined in Table 7-1). The easiest way to remedy this would be to develop flow records for some of the sites that do not have an associated flow record currently. Similarly, more sites in the high nutrient enrichment category would provide a more complete dataset, especially sites with high flow variability.

7.2.2 Data collection: 3. Monitor periphyton

The discussion in Section 7. 1 above covers this step. Periphyton data collection that is suitable for assessing a site against the NPS_FM periphyton attribute should also be suitable for developing models.

7.2.3 Data collection: 4. Collect data on controlling factors

The NRC dataset included most of the key variables known to be important in controlling periphyton. Histograms of the all predictor variables used are presented in Appendix E to illustrate their distributions. Some variables likely reflect conditions in Northland, such as Tmean (biased towards higher values), Pccoarse (biased towards low values) and mean flow (biased towards small streams). We note that all of the Northland sites are in relatively small rivers compared to those in other datasets (e.g., Horizons and Canterbury regions, Appendix C).

We have three suggestions for improving the dataset.

First, 13 of the 39 sites were not covered by the final relationships because they lacked flow data (Table 5-4, and refer to Appendix A for identification of the omitted sites). Modelled flow records may be useful to enable flow-based predictor variables to be calculated for all sites. Note that using metrics based on national predictions such as TopNet (Booker and Woods 2014) are not always precise enough at the reach scale to be useful, although they show broad patterns well. In a recent nationwide analysis of periphyton (Kilroy et al. 2019), TopNet flow records were generated for all sites including those in Northland. TopNet and actual records did not correspond closely enough over the national dataset to provide confidence in using the data at specific ungauged sites for detailed analyses (such as derivation of an effective flow). However, a more detailed evaluation at the Northland sites would be useful to confirm the degree of correspondence between actual and TopNet modelled data in Northland.

Flow metrics were not as important predictors in Northland as they have been in other regions. However, distinguishing flow-sensitive from flow-insensitive sites enabled identification of good models. Currently the best way to make the distinction is to use empirical data on periphyton relative to preceding flows and accrual periods. Hoyle et al. (2017) provided an objective method for distinguishing high (substrate) mobility sites from low mobility sites, but this also requires a flow record, as well as detailed field measurements.

The second suggestion was made in Section 5.4.3 in view of the apparent importance of water temperature in influencing periphyton abundance in Northland. It was suggested the collection of continuous water temperature data could be helpful in producing more accurate and representative water temperature data than that based on monthly spot measurements. The simplest action would be to add temperature sensors to existing water level recorders.

The third suggestion is to provide a continuous variable to represent shade. Light at the streambed has been identified as an important predictor of periphyton in previous studies (Matheson et al. 2012, Snelder et al. 2014). A large component of variability in light arises from riparian shading. Matheson et al. (2012) provided details on the calculation of light at the streambed using shade, water clarity, water depth, absorbance of the water, and incident light.

In summary, NRC's periphyton dataset covers a reasonably good range of sites in terms of flow variability and nutrient enrichment and is therefore already suitable for preliminary development of periphyton – environment relationships (as presented in this report). The dataset would benefit from the addition of more sites with a flow record, as the number of sites with complete data (all variables) is small (n = 21). The current sites with no flow record span a range of nutrient enrichment. Therefore, development of flow records for some or all of these would be helpful. More rigorous measurement of both water temperature and shade (or light availability) could also help to improve the performance of the relationships.

8 Synthesis and recommendations

In this Envirolink-funded report we addressed three questions put to NIWA by NRC, using a dataset of monthly periphyton and linked environmental variables collected by NRC since January 2015.

8.1 Compliance with guidelines

> *"Is there a problem with periphyton in Northland (as determined from exceedances of MfE guidelines and breaches of the "national bottom line" (D band) of the periphyton attribute in the National Policy Statement for Freshwater Management (NPS-FM))? The analysis will include identification of problem sites for periphyton growth measured as both chlorophyll a biomass and percentage cover and including cyanobacteria."*

8.1.1 MfE 2000 guidelines

Percentages of sites not complying with the MfE 2000 guidelines over the period of monthly monitoring (January 2015 to May 2018) ranged from 90% (35 of 39 sites) for mean chlorophyll *a* to protect benthic biodiversity (< 15 mg/m^2) to 33% for the highest threshold (maximum chlorophyll *a* < 200 mg/m^2).

The sites least compliant relative to the MfE standards for percentage cover (aesthetics / recreation values) were **Hakaru at Topuni**, **Opouteke at Suspension Bridge**, **Oruaiti at Sawyer Road** and **Waipapa at Landing** (for percentage cover by filaments) and **Pekapeka at Ohaeawai** and **Waipapa at Waimate North Road** (for percentage cover by mats).

Thresholds set in the MfE 2000 guideline to protect benthic biodiversity were exceeded most often and by the highest margins at **Hakaru at Topuni**, **Pekapeka at Ohaeawai**, **Opouteke at Suspension Bridge**, and **Waipapa at Landing** (for the 50 mg/m^3 threshold). The same sites excluding Pekapeka at Ohaeawai, but including **Awanui at FNDC**, **Waiharakeke at Stringers Road** and **Punakitere at Taheke** also had mean annual chlorophyll *a* (from monthly samples) on average at least four-fold greater than the threshold of 15 mg/m^3.

Two sites (**Hakaru at Topuni**, **Waiharakeke at Stringers Road**) had persistent high chlorophyll *a* that breached the MfE 2000 guidelines for protection of trout habitat and angling (120 and 200 mg/m^2 thresholds) in the three consecutive years with complete data.

8.1.2 NPS-FM periphyton attribute

Thirty-two sites (82%) were graded into bands A or B of the NPS-FM periphyton attribute, and two sites (5%) into band D. The band D sites were **Hakaru at Topuni** and **Waiharakeke at Stringers Road**. Five sites graded as band C generally coincided with those exceeding MfE guidelines but included **Watercress at SH1**.

8.1.3 Cyanobacteria guideline

The Alert level of the cyanobacteria guideline (20% cover) was exceeded at one-third of all sites from 2015 to 2018, and the Action level (50% cover) was exceeded at least once at four sites. One site (**Ruakaka at Flyger Road**) had exceedances in three years. Three sites had exceedances in two years: **Kerikeri at Stone Store**, **Ngunguru at Coalhill Lane**, **Opouteke at Suspension Bridge**. Cyanobacteria cover is widespread in Northland with observations of some cover at 32 of the 39 sites (82%) between January 2015 and May 2018.

8.2 Drivers of periphyton biomass in Northland rivers

"What are the major drivers of periphyton growth in Northland? In particular, what are the roles of dissolved inorganic nitrogen (DIN), dissolved reactive phosphorus (DRP) and ammoniacal-N (NH4-N) in driving periphyton and what are appropriate instream nutrient criteria for Northlands hard-bottomed rivers?"

Relationships between periphyton (the 92nd percentile of chlorophyll *a*, Chla_92) and environmental variables were explored using regression techniques. Environmental variables that contributed to strong predictive relationships were: mean water temperature, DRP, DIN, flow metrics and substrate (percentage of the bed covered by coarse substrate). Water temperature appeared to be the strongest predictor. DRP was generally a stronger predictor than DIN, although relationships with either DRP or DIN as predictors were identified. Catchment geology (represented by the REC geology class) influenced periphyton – environment relationships.

NH_4-N concentration (NH4N) and NH_4-N as a percentage of DIN (pcNH4) were, respectively, positively and negatively strongly correlated with DIN across all sites. There were also correlations between pcNH4 or NH4N and DRP across subsets of sites. The strong correlations meant that it was not possible in this analysis to isolate any effect of NH_4-N on Chla-92 from the effect of DIN or DRP.

We suggest that further analysis of the monthly time-series of DRP, DIN and NH_4-N (rather than using three-year means) may assist in understanding site-specific responses.

No relationship had predictive skill across all 39 sites. Chla_92 was predictable only across smaller subsets of sites, which included:

- sites at which periphyton was sensitive to flow (identified using within-site analyses);
- sites with catchments dominated by hard sedimentary geology (HS geology class in the REC);

We provide preliminary derivations of nutrient criteria (both DRP and DIN) using five relationships with predictive skill defined as Good or Excellent (based on a published scale). The criteria apply to Chla_92 of 50, 120 and 200 mg/m^3 (the thresholds separating the NPS-FM periphyton bands) for Chla_92 set at the predicted value, and at the upper limit of the 95% confidence interval (UCL). The UCL provides more conservative (i.e., restrictive) nutrient criteria but increases confidence that the Chla_92 threshold will not be exceeded.

Each set of criteria applies to predefined combinations of values of predictor variables (selected based on the range of values of each predictor in the dataset used to develop the relationship) across a defined subset of sites. Look-up diagrams are provided for all five relationships. Calculations were performed in spreadsheets, which can be provided to NRC if required.

It is stressed that the relationships used to derive the nutrient criteria were derived from small datasets. Reliability could be improved with expansion of the datasets.

8.3 Review of Northland's periphyton monitoring programme

"Is Northland's current periphyton monitoring programme fit for purpose, in relation to (a) setting numeric freshwater periphyton objectives for Northland's rivers, and (b) monitoring progress towards the achievement of the freshwater objectives in the context of the NPS-FM?"

Related to question (b), which is the primary purpose of the programme, we concluded that the size of the programme (number of sites) is good compared to the size of the region. Site representation appeared to be good, although a detailed assessment of representativeness was beyond the scope of this project. Our understanding is that sample collection methods are adequate because they follow standard procedures. Sample analysis methods (for chlorophyll *a*) are consistent with those used by at least three other regions.

Related to question (a), we reviewed suitability of the dataset for model development by referring to three steps towards development of nutrient limits suggested in MFE (2018): (1) select suitable periphyton monitoring sites; (2) monitor periphyton; (3) collect data on controlling factors.

To assess step (1) we placed all existing sites in a matrix of flow variability (represented by FRE3, the mean annual frequency of events greater than three times median flow) versus nutrient enrichment. The outcome was that NRC's periphyton dataset covers a reasonably good range of sites in terms of flow variability and nutrient enrichment and is therefore already suitable for preliminary development of periphyton – environment relationships (as presented in this report). However, the number of sites lacking flow data constrained model development. Regarding step (2), we considered that this step was addressed by question (b) above. For step (3) the NRC dataset already includes data on most of the important potential controllers of periphyton. Three recommendations were made for improvements.

8.4 Summary of recommendations

The following three recommendations are aimed at improving the dataset, to enable development of more reliable relationships for deriving nutrient criteria.

- Development of relationships covering all sites was constrained by lack of flow data at 18 of the sites. We suggest that modelled flow records would be useful to enable flow-based predictor variables to be calculated for all sites. Flow predictions already exist in the national model TopNet (Booker and Woods 2014) and a first step would be to evaluate TopNet predictions against existing flow records in Northland.
- In view of the apparent importance of water temperature in influencing periphyton abundance in Northland, we suggest that more accurate water temperature data would be useful to supplement the existing monthly spot temperature measurements, which are potentially biased. As a start, continuous water temperature loggers (15 min to 1 hourly data collection) could be installed at existing water level recorders.
- A continuous variable to represent shade would be useful in view of the importance of light at the streambed as a predictor of periphyton in previous studies.

The following comments following the analysis of periphyton – environment relationships were also made, but as suggestions for further research rather than recommendations:

- It may be useful to explore seasonal patterns of nutrient concentrations (DIN, DRP and NH_4-N), flows and periphyton biomass within sites (i.e., using the monthly time-series data) to improve understanding of their inter-relationships.
- Lack of relationship between periphyton biomass and EC was interesting in view of strong correlations in other regional datasets and could warrant further investigation.

9 Acknowledgements

This report was funded through the MBIE Envirolink Fund (Medium Advice Grant, 1910-NLRC207, contract C01X1808). Thanks to Carol Nicholson (Northland Regional Council) for initiating the project, and Ben Tait (NRC) for further discussions. We also thanks Carol and Gail Townsend (NRC) for provision of the various datasets. Kath Walter (NIWA) processed the flow data ready for analysis, Michelle Greenwood provided the R code used for the regression analyses, and Amber Sinton prepared the map. We thank Clive Howard-Williams for his helpful review.

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Appendix A Northland Regional Council periphyton monitoring sites: summary of data

N is site number as shown on Figure 2-1, in order from north to south. Sites are colour-coded to show their placement in an NPS-FM periphyton attribute band, based on data from January 2015 to December 2017 (see Section 3) (blue, band A; green, band B; amber, band C; red, band D). The 92nd percentile of chlorophyll *a* at each site (Chla_92) was calculated including adjustment for missing data, based on the assumption that missing data corresponded to times of high flows when correction. Under EC, * shows two sites with tidal (sea water) influence.

Shaded cells indicate groups of sites for which potentially useful relationships including DIN or DRP were developed (blue: flow-sensitive site; brown: flow-insensitive; lilac, HS geology; grey, lowland, flow-sensitive).

				River flows					Nutrients (mg/m³)					Other WQ				Substrate		Shade	REC	
N	**Site Name**	**Chla_92**	**% mis-sing**	**EF**	**DaEF**	**Da3**	**Nneg**	**Rever-sals**	**DIN**	**DRP**	**NH4-N**	**TN**	**TP**	**pcNH4**	**EC**	**T-mean**	**Turb**	**Pc sand**	**Pc coarse**		**Geol-ogy**	**Slope**
5	Awanui at FNDC	173	33	8	38	18	270	116	13	19	13	228	42	42	167	16.6	5.8	5	45	full sun	SS	H
39	Hakaru at Topuni	717	20			25	252	114	91	60	26	580	103	23	166	16.0	5.5	0	100	full sun	SS	L
32	Hatea at Mair Park	15	11			25	256	127	363	13	18	594	24	6	7124*	16.1	3.9	5	40	partial	VA	L
4	Kaeo at Dip Road	27	6						15	9	11	160	20	40	117	16.0	4.3	15	0	full sun	SS	H
36	Kaihu at Gorge	67	6	5	64	30	244	132	111	7	7	290	16	11	101	15.3	3.1	5	20	partial	VA	L
11	Kerikeri at Stone Store	63	6	19	67	22	271	125	313	10	22	523	25	8	621*	16.7	2.3	5	60	full sun	VA	L
25	Mangahahuru at Main Road	23	6			35	265	128	123	13	12	252	28	11	84	14.5	7.1	15	0	partial	HS	H
24	Mangakahia at Twin Bridges	97	11	3	23	23	261	128	22	9	6	169	18	28	102	16.8	4.2	5	25	full sun	VA	H
28	Mangakino at Mangakino Lane	38	4						168	12	6	304	25	4	89	14.3	8.8				VA	L
10	Mangamuka at Iwitaua Road	22	11						6	31	6	82	44	47	131	15.2	2.0	15	0	full sun	SS	H
26	Ngunguru at Coalhill Lane	77	4	8	53	27	272	136	77	14	11	262	30	16	90	16.8	4.2	25	0	full sun	HS	H
29	Opouteke at Suspension Bridge	154	21	17	70	21	256	132	43	9	6	213	17	22	126	16.9	3.4	0	10	full sun	VA	H
3	Oruaiti at Sawyer Road	107	15						10	12	7	170	23	41	132	16.0	3.7	10	5	full sun	SS	H
1	Oruaiti at Windust Road	62	8						32	12	10	236	27	27	124	16.2	4.7	30	0	full sun	VA	H
37	Otaika at Otaika Valley Road	53	3	5	52	32	263	129	1057	22	21	1387	42	2	191	15.4	7.3	15	0	partial	HS	L

N	Site Name	Chla _92	% mis-sing	EF	DaEF	Da3	Nneg	Rever -sals	DIN	DRP	NH4-N	TN	TP	pcNH 4	EC	T-mean	Turb	Pc sand	Pc coarse	Shade	Geol-ogy	Slope
				River flows					Nutrients (mg/m³)						Other WQ			Substrate		Shade	REC	
18	Pekapeka at Ohaeawai	85	0						238	10	9	375	17	6	99	16.0	2.4	0	50	full sun	VA	L
6	Peria at Honeymoon Valley Road	110	0						16	48	4	66	54	25	130	13.8	2.0	10	30	partial	VA	H
31	Pukenui at Kanehiana Drive **	3	1						105	17	11	182	28	9	169	14.0	4.9	10	10	partial		
22	Punakitere at Taheke	133	42	1.5	21	23	269	111	209	21	17	627	46	12	114	16.4	5.6	30	50	full sun	SS	L
20	Punaruku at Russell Road **	9	5						14	11	5	115	15	25	86	15.2	1.5	10	0	partial	HS	H
35	Raumanga at Bernard Street	47	4	7	65	27	247	151	1029	17	17	1244	27	2	188	15.6	2.5	10	50	full sun	VA	L
38	Ruakaka at Flyger Road	63	3	6	35	25	257	121	334	92	68	850	150	14	200	15.1	9.4	20	0	shaded	SS	L
2	Stony Creek at Sawyer Road	25	3						40	14	15	252	27	27	112	16.4	4.2	10	20	partial	VA	L
8	Tapapa at SH1 **	5	9						15	40	4	89	50	25	134	14.3	1.7	15	15	partial	VA	H
7	Victoria at Victoria Valley Road	31	6	7	51	22	271	126	5	21	5	85	29	46	135	15.0	2.0	10	0	partial	VA	H
33	Waiarohia at Second Avenue	113	6	6	40	22	250	150	250	13	15	417	27	10	222	16.7	2.6	15	10	full sun	HS	H
30	Waiarohia at Whau Valley	66	4						424	16	13	595	28	4	256	15.2	2.3	10	0	partial	HS	L
16	Waiaruhe at Puketona	54	7						141	12	22	432	29	14	111	16.0	4.8	20	40	full sun	HS	L
19	Waiaruhe d/s Mangamutu Confl.	52	20						397	9	105	789	22	20	143	16.0	5.4	30	0	full sun	SS	L
21	Waiharakeke at Stringers Road	251	31	3	27	27	259	80	69	16	38	553	48	26	135	16.2	7.9	30	20	partial	SS	L
23	Waimamaku at SH12	30	16						4	6	5	117	11	52	97	15.9	3.1	5	5	full sun	VA	H
34	Waipao at Draffin Road	54	6			52	228	151	2336	35	24	2693	53	1	170	15.9	2.6	5	5	full sun	VA	L
12	Waipapa at Forest Ranger	32	8	13	55	20	273	114	24	5	4	137	13	28	120	15.5	2.4	10	0	full sun	HS	L
9	Waipapa at Landing	160	6						207	5	16	433	13	11	87	17.0	2.2	0	95	full sun	VA	L
13	Waipapa at Waimate North Road	34	5						48	17	20	401	42	28	74	16.1	3.3	0	100	full sun	VA	L
27	Waipoua at SH12	4	1			23	240	126	15	6	7	97	10	29	78	14.1	2.5	5	25	partial	VA	H
15	Waitangi at SH10	30	39	2	34	36	258	131	120	9	15	347	24	15	104	16.0	4.2	15	0	full sun	VA	L
14	Waitangi at Waimate North Road	32	23	6	50	26	271	125	277	6	14	464	21	5	92	15.5	5.5	15	0	full sun	VA	L
17	Watercress at SH1	154	12						757	30	15	898	53	2	134	16.8	2.3	20	40	partial	HS	L

Appendix B Pearson correlation matrix of all predictor variables and 92nd percentile of chlorophyll *a*

The correlations were calculated from dataset B (see Section 2.5) using all available data. For example, maximum n = 39 for most of the water quality and nutrient correlations, but maximum n = 16 for correlations with DaEF. Correlations >0.6 or <-0.6 are highlighted with grey shading. Blue-shaded variables were dropped from the regression analysis. EC data at the two tidally influenced sites (Hatea at Mair Park, Kerikeri at Stone Store) were omitted from the correlation analysis.

	DO%	pH	Clarity	Tmean	Tmin	Tmax	DRP	DIN	TN	TP	NH4-N	pcNH4	Nneg	Reversals	EC	Turbid	DaEF	Da3	Da7	Da13	Pcfine	Pccoarse	Pcsand	TNtoTP	DINtoDRP
pH	0.30	1.00																							
Clarity	0.35	0.16	1.00																						
Tmean	0.03	-0.04	0.08	1.00																					
Tmin	0.07	-0.04	-0.15	0.30	1.00																				
Tmax	0.17	0.20	0.07	0.75	-0.07	1.00																			
DRP	-0.25	0.21	-0.27	-0.22	0.24	-0.35	1.00																		
DIN	0.06	-0.30	0.05	0.18	0.42	-0.11	0.14	1.00																	
TN	0.03	-0.28	-0.11	0.37	0.43	0.11	0.21	0.92	1.00																
TP	-0.32	0.07	-0.33	-0.06	0.18	-0.21	0.94	0.25	0.36	1.00															
NH4-N	-0.21	-0.41	-0.23	0.31	0.21	0.12	0.23	0.73	0.79	0.43	1.00														
pcNH4	-0.17	0.24	-0.11	0.00	-0.43	0.28	-0.08	-0.90	-0.75	-0.13	-0.42	1.00													
Nneg	-0.27	-0.05	0.06	0.21	-0.27	0.28	-0.18	-0.37	-0.38	-0.03	-0.09	0.35	1.00												
Reversals	0.32	-0.04	0.25	-0.01	0.52	-0.24	-0.05	0.40	0.21	-0.22	-0.11	-0.51	-0.43	1.00											
EC	0.02	0.32	-0.06	-0.01	0.37	-0.12	0.52	0.40	0.41	0.49	0.39	-0.27	-0.24	0.20	1.00										
Turbid	-0.11	-0.24	-0.66	-0.01	-0.07	0.15	0.15	0.24	0.35	0.36	0.52	-0.12	0.25	-0.53	0.06	1.00									
DaEF	0.31	0.16	0.54	-0.21	-0.05	-0.28	-0.30	0.15	-0.03	-0.43	-0.23	-0.29	-0.11	0.48	0.04	-0.54	1.00								
Da3	0.07	-0.46	-0.09	-0.25	0.21	-0.37	0.22	0.60	0.58	0.21	0.28	-0.59	-0.54	0.33	0.00	0.10	-0.03	1.00							
Da7	0.22	-0.18	-0.12	-0.21	0.18	-0.15	-0.39	0.08	-0.04	-0.45	-0.28	-0.22	-0.44	0.28	-0.34	-0.13	-0.15	0.39	1.00						
Da13	-0.43	-0.48	-0.15	-0.23	0.02	-0.14	-0.19	-0.19	-0.34	-0.18	-0.19	0.13	-0.23	0.17	-0.36	-0.05	-0.21	0.36	0.34	1.00					
Pcfine	-0.34	-0.42	-0.35	-0.06	-0.18	0.06	-0.03	0.07	0.07	0.10	0.35	0.04	0.28	-0.11	0.09	0.43	-0.36	0.26	0.12	0.37	1.00				
Pccoarse	-0.02	0.03	0.14	0.32	0.02	0.12	0.10	0.17	0.24	0.16	0.17	-0.13	-0.09	-0.20	-0.17	-0.10	-0.05	-0.30	-0.38	-0.33	-0.67	1.00			
Pcsand	-0.29	-0.28	-0.34	0.02	-0.12	-0.03	0.16	0.13	0.15	0.29	0.28	-0.02	0.35	-0.38	0.12	0.43	-0.56	0.07	0.03	-0.01	0.74	-0.43	1.00		
TNtoTP	0.24	-0.33	0.11	0.42	0.32	0.25	-0.43	0.77	0.78	-0.30	0.52	-0.68	-0.43	0.45	0.09	0.11	0.33	0.52	0.35	-0.21	0.01	0.13	-0.04	1.00	
DINtoDRP	0.19	-0.38	0.16	0.26	0.31	0.04	-0.27	0.92	0.81	-0.13	0.58	-0.88	-0.30	0.44	0.15	0.18	0.29	0.52	0.28	-0.10	0.08	0.13	0.06	0.92	1.00
Chla_92	0.06	0.13	-0.09	0.61	0.13	0.42	0.20	0.22	0.39	0.33	0.31	-0.07	0.10	-0.31	0.23	0.22	-0.37	-0.15	-0.38	-0.31	-0.10	0.39	0.04	0.17	0.14

Appendix C Comparison of data from Northland, Manawatu-Whanganui and Canterbury

Regional statistics (N, minimum, maximum, median, mean, standard deviation) are shown for the main variables used in the analyses. Nutrient statistics were calculated from geometric means at each site. Lines with median values are highlighted in grey to aid comparisons. *Note that in the Northland dataset, conductivity values from two sites known to have tidal influence were removed from the dataset (Hatea at Mair Park, Kerikeri at Stone Store).

Statistic	Periphyton		Temperature					EC (µS/cm)	Nutrients (mg/m^3)				Substrate			Flow (m^3/s)		Accrual (days)		
	Chla_ mean	Chla_ 92	mean	max	min	med	range	mean	DRP	DIN	TN	TP	Pc-coarse	Pc-fine	Pc-sand	mean	med	Da_ EF	Da_ 3med	Da_ 10med
Northland Regional Council																				
N	38	38	38	38	38	38	38	36	38	38	38	38	37	37	37	21	21	12	21	21
Min.	0.6	4.3	13.9	18.7	5.8	13.7	7.1	60.4	4.7	3.2	66.3	9.7	0.0	0.0	0.0	0.4	0.2	15.4	14.6	31.4
Max.	96.7	717.0	17.3	24.2	11.8	17.3	17.8	233*	94.0	2393	2694	151.4	100.0	100.0	30.0	9.6	5.1	432	432	3894
Med.	7.2	54.3	16.1	21.6	9.7	16.1	12.1	112	12.5	88.9	293	25.7	10.0	35.0	10.0	1.4	0.7	38.6	18.6	60.5
Mean	11.9	86.0	15.9	21.6	9.6	15.9	12.0	121	18.4	245	442	31.8	23.2	42.2	12.0	2.7	1.4	91.2	38.6	244
SD	16.5	118.5	1.0	1.5	1.2	1.0	1.9	41.0	17.6	444	487	25.6	29.3	27.4	8.9	2.7	1.4	127	88.0	816
Horizons Regional Council (Manawatu-Whanganui region)																				
N	61	61	61	61	61	61	61	61	59	59	56	56	61	61	61	45	45	37	45	45
Min.	0.2	2.0	8.5	10.7	2.9	8.2	5.0	52.0	4.9	5.8	55.1	0.0	0.0	17.0	0.0	0.5	0.3	14.0	9.9	32.3
Max.	52.1	220	17.3	24.7	9.5	18.3	19.2	335	188	1480	1853	255	40.0	62.0	13.0	103	67.2	287.3	41.1	433
Med.	3.0	40.5	12.6	19.2	6.5	11.7	13.0	117	10.5	186	493	20.6	12.0	30.0	2.0	6.7	4.1	37.4	19.3	86.4
Mean	9.6	60.8	12.3	18.9	6.4	11.9	12.5	136	16.3	339	571	29.0	14.0	31.4	2.4	22.3	14.3	51.1	20.0	155
SD	12.4	55.1	2.1	3.6	1.5	2.2	3.2	66.7	24.8	386	437	34.7	9.5	9.3	2.4	31.9	21.2	48.1	6.7	118
Environment Canterbury																				
N	24	24	24	24	24	24	24	24	24	24			24	24	24	24	24	24	24	24
Min.	0.1	6.1	8.0	14.3	1.2	9.0	11.1	21.2	1.1	9.3			0.0	21.0	1.0	1.2	0.5	13.3	23.9	57.7
Max.	24.2	271.1	14.5	22.6	7.1	15.8	18.6	300	23.1	4132			16.0	59.0	12.0	204	151	111	55.9	790
Med.	2.6	79.7	11.8	18.7	4.0	12.3	14.9	85.0	2.9	134			2.5	38.5	6.5	5.9	3.4	52.5	34.8	117
Mean	4.3	96.5	11.7	18.7	3.9	12.1	14.9	103	4.4	502			4.0	38.0	6.4	29.5	20.7	51.7	36.4	203
SD	5.5	76.3	1.5	2.1	1.6	1.6	2.4	63.0	4.5	903			4.3	11.6	3.4	50.0	37.6	25.6	7.0	186

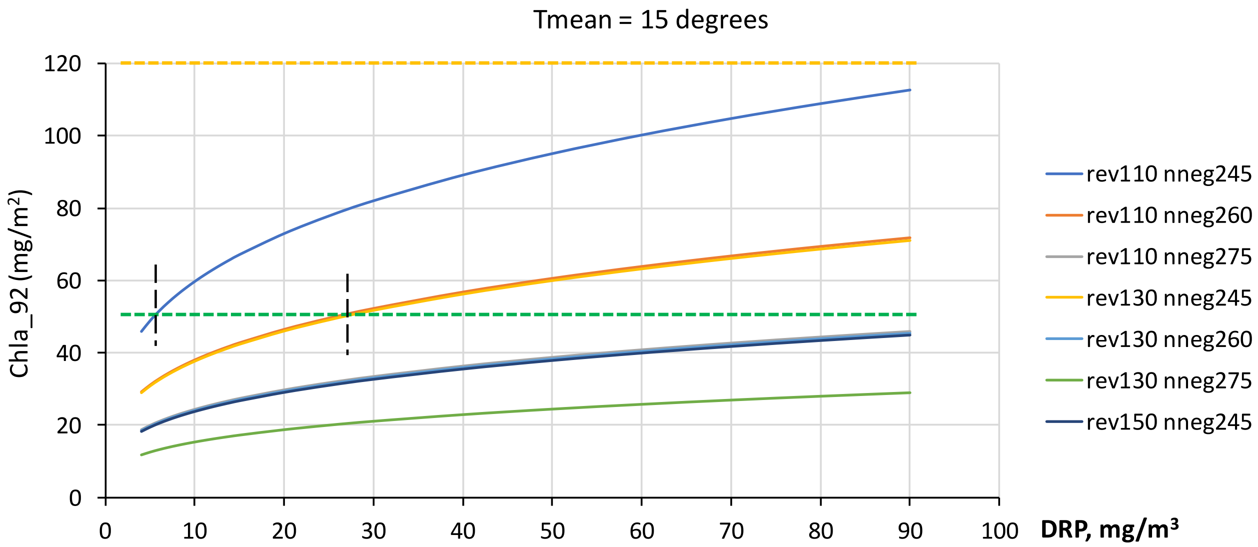
Appendix D Predictions of Chla_92 plotted against DRP and DIN under different combinations of predictor values

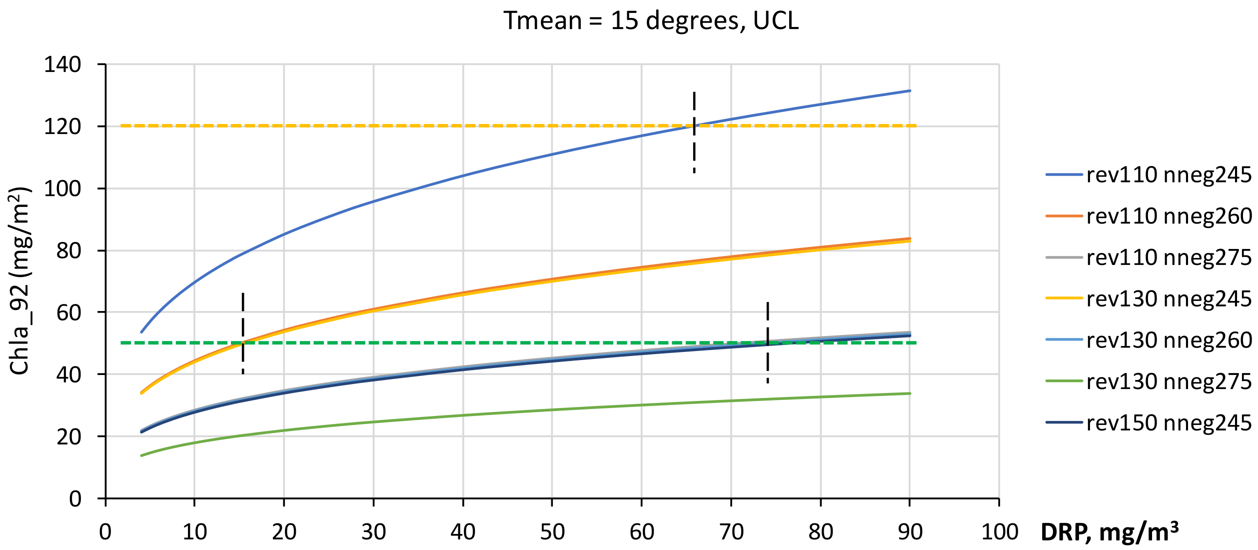
The models listed in Table 5-4 were used to make predictions of Chla_92 for a range of DRP and DIN using values of predictor variables based on the range in the dataset used to develop the relationships. Values and combinations outside the range of the data were avoided as far as was possible.

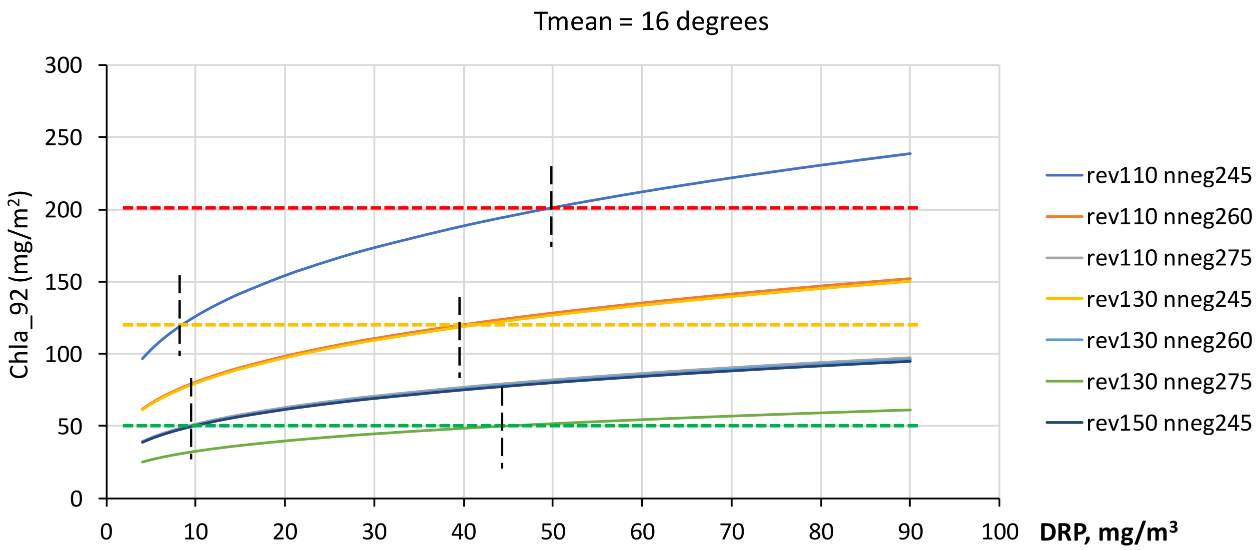
Two sets of predictions are plotted for each model: the model estimate, and the upper limit of the 95% confidence interval (UCL). The UCL provides more conservative (i.e., restrictive) limits.

On each look-up plot, the green, amber and red dashed lines highlight the NPS-FM thresholds: Chla_92 of 50, 120 and 200 mg/m^2. Limits for DRP and DIN corresponding to the thresholds were read off where possible. Vertical black dashed lines show where limits were read off the plots. Note that the vertical scales may vary.

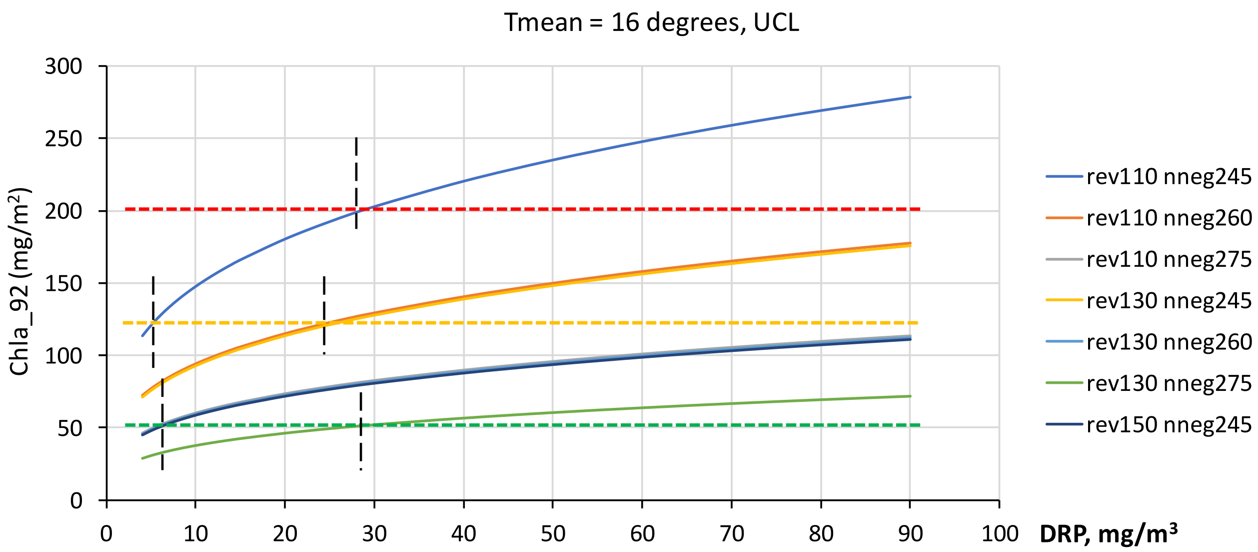
Model 9: Flow-sensitive sites: three plots, one each for Tmean = 15, 16 and 17 °C. Rev = reversals



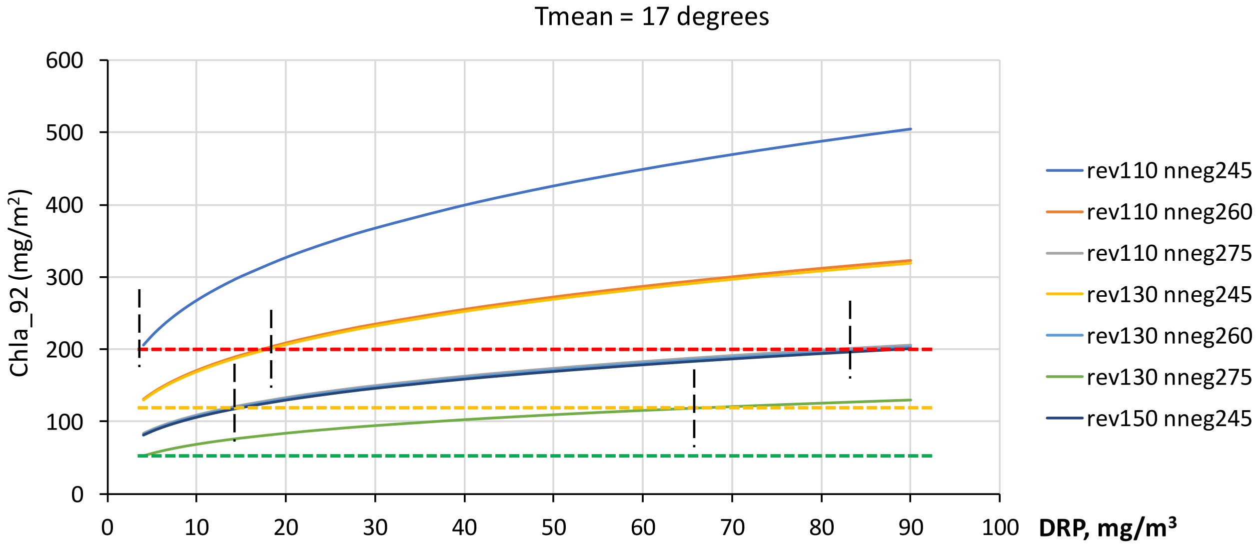


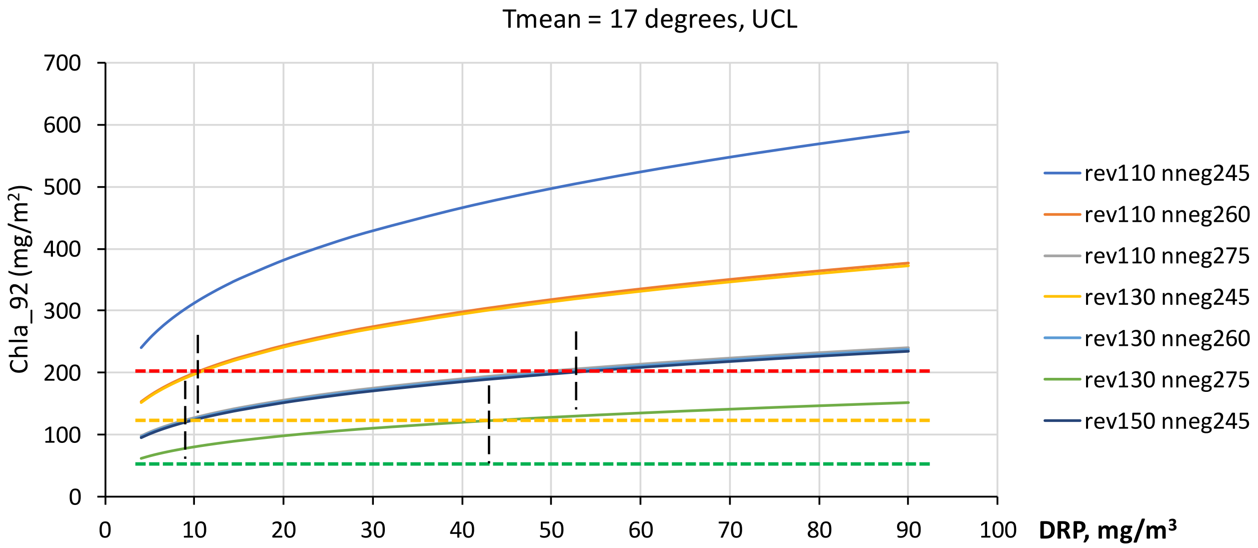


Tmean = 16 degrees
Chla_92 (mg/m2)
300
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
100
DRP, mg/m3
rev110 nneg245
rev110 nneg260
rev110 nneg275
rev130 nneg245
rev130 nneg260
rev130 nneg275
rev150 nneg245



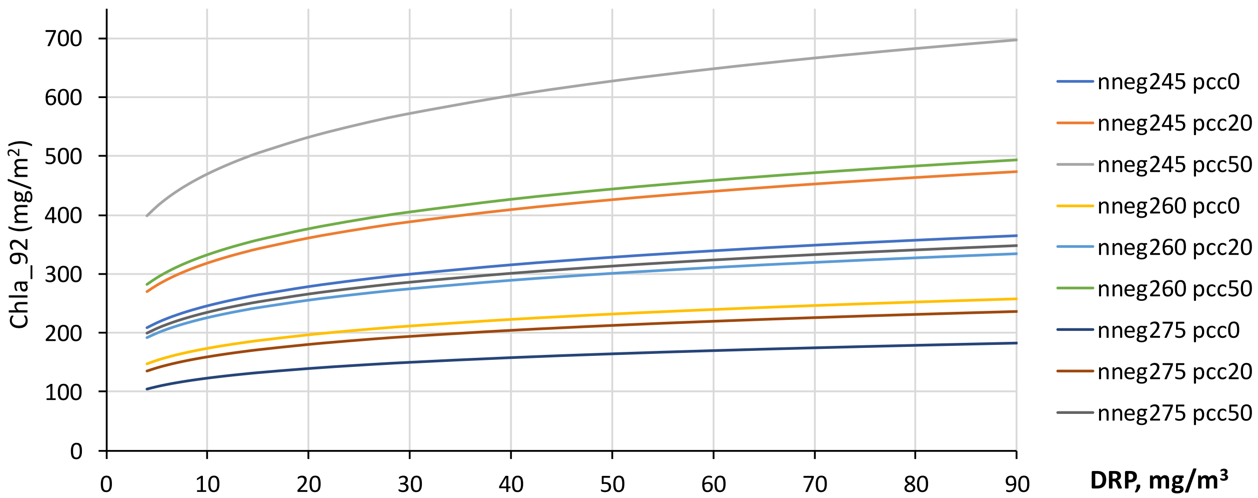
Tmean = 16 degrees, UCL
Chla_92 (mg/m2)
300
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
100
DRP, mg/m3
rev110 nneg245
rev110 nneg260
rev110 nneg275
rev130 nneg245
rev130 nneg260
rev130 nneg275
rev150 nneg245


Tmean = 17 degrees
Chla_92 (mg/m²)
DRP, mg/m³
rev110 nneg245
rev110 nneg260
rev110 nneg275
rev130 nneg245
rev130 nneg260
rev130 nneg275
rev150 nneg245

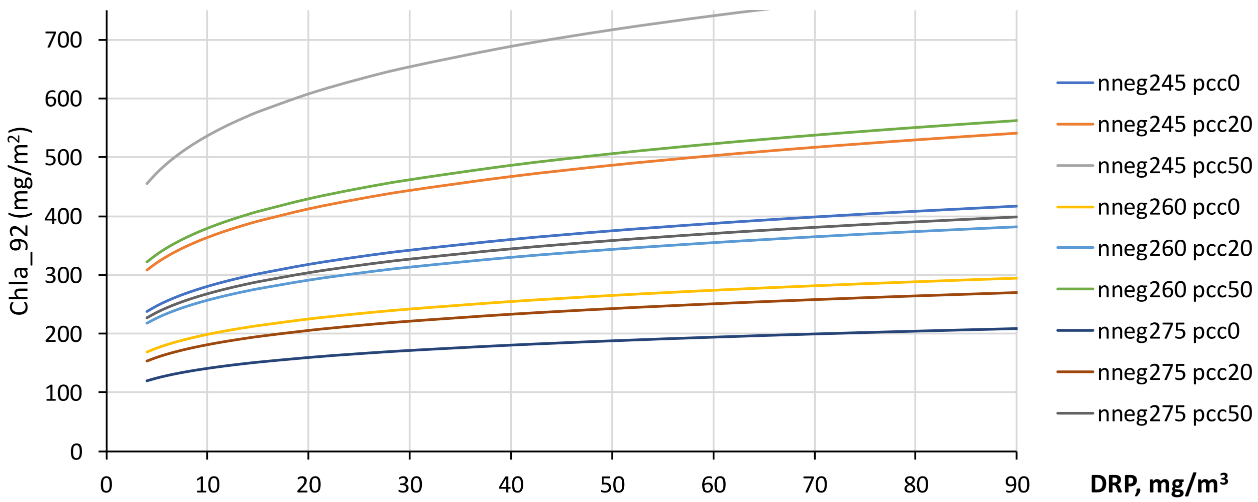

Tmean = 17 degrees, UCL
Chla_92 (mg/m²)
DRP, mg/m³
rev110 nneg245
rev110 nneg260
rev110 nneg275
rev130 nneg245
rev130 nneg260
rev130 nneg275
rev150 nneg245

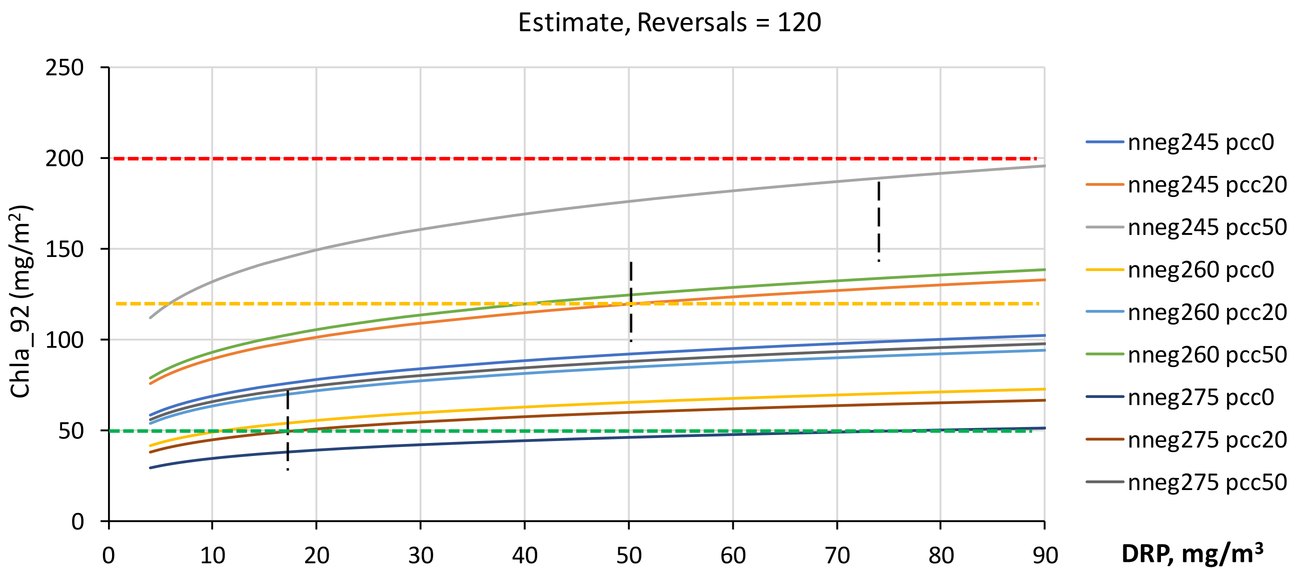
Model 25b. Flow-sensitive, lowland sites, DRP as nutrient predictor: three plots, one each for Reversals = 90, 120 and 150 /year. Pcc = pccoarse

Estimate, Reversals = 90

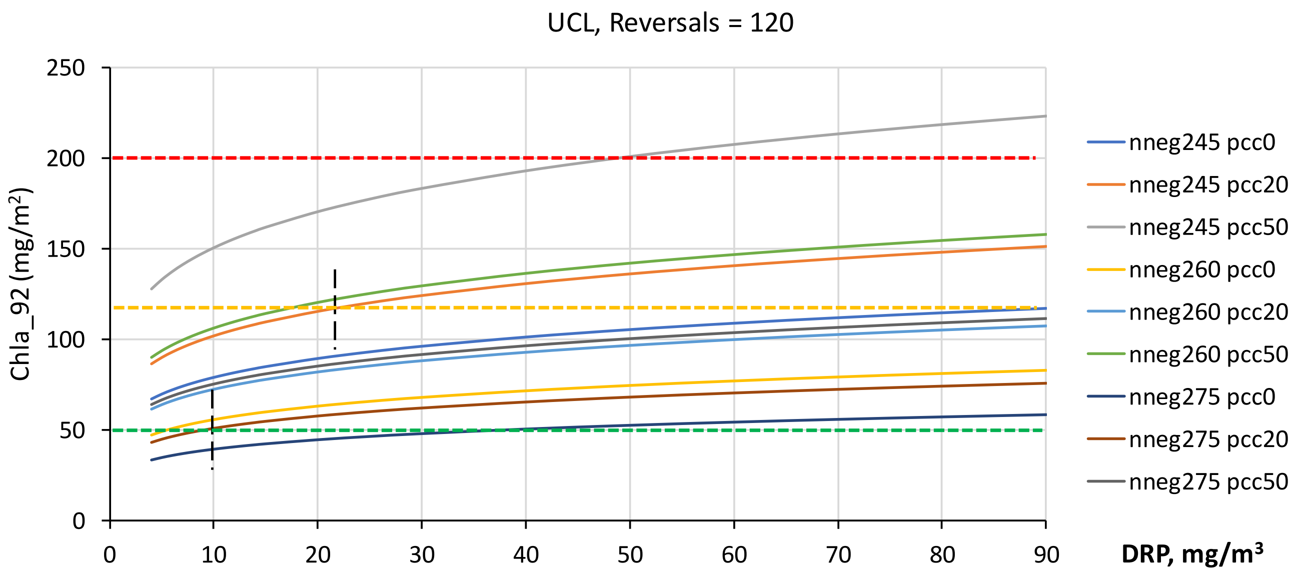


UCL, Reversals = 90



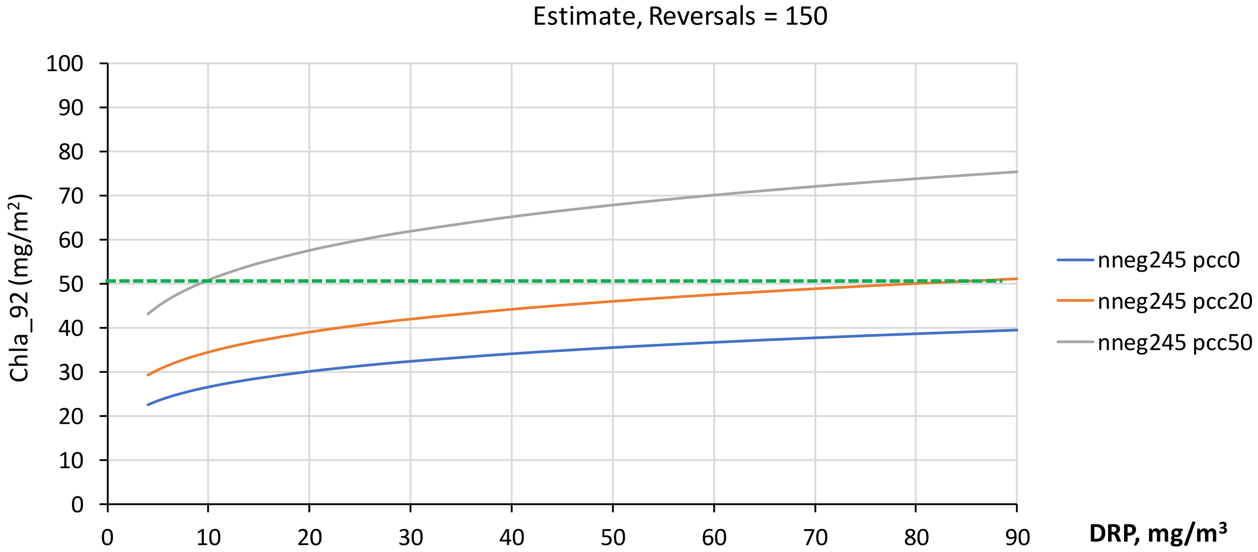


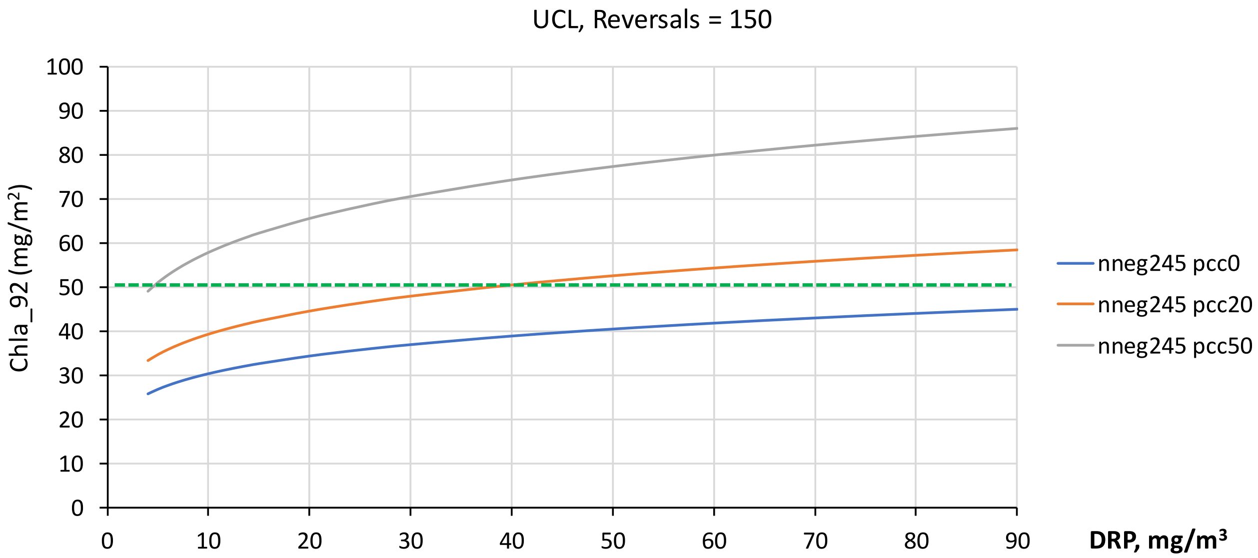
Estimate, Reversals = 120
Chla_92 (mg/m²)
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
DRP, mg/m³
nneg245 pcc0
nneg245 pcc20
nneg245 pcc50
nneg260 pcc0
nneg260 pcc20
nneg260 pcc50
nneg275 pcc0
nneg275 pcc20
nneg275 pcc50



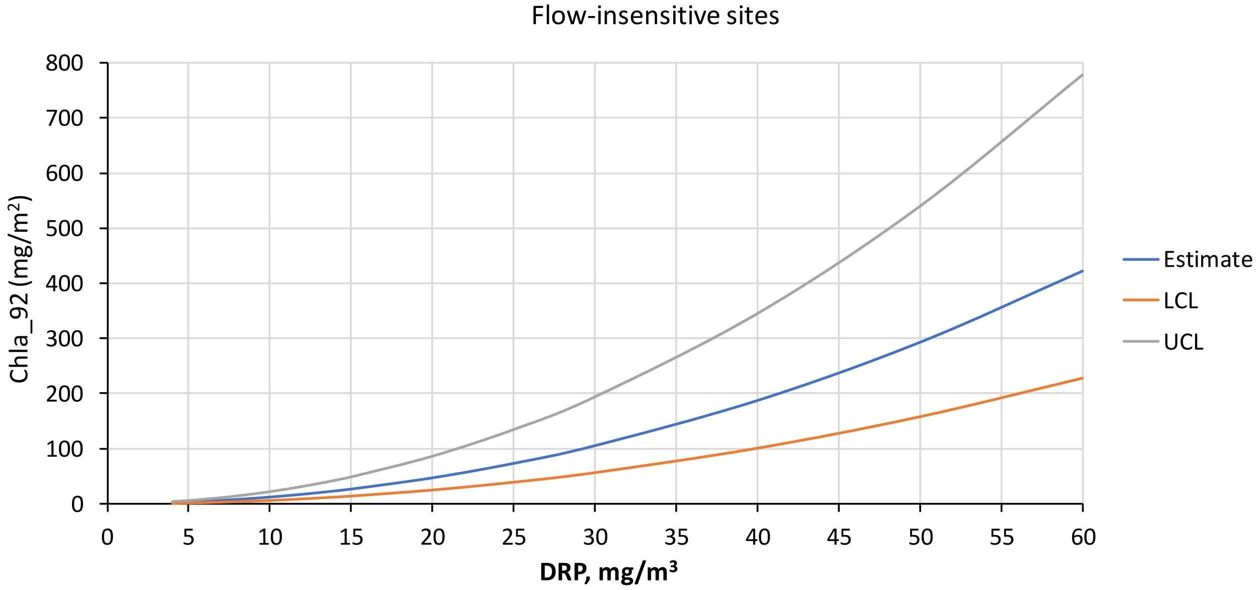
UCL, Reversals = 120
Chla_92 (mg/m²)
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
DRP, mg/m³
nneg245 pcc0
nneg245 pcc20
nneg245 pcc50
nneg260 pcc0
nneg260 pcc20
nneg260 pcc50
nneg275 pcc0
nneg275 pcc20
nneg275 pcc50

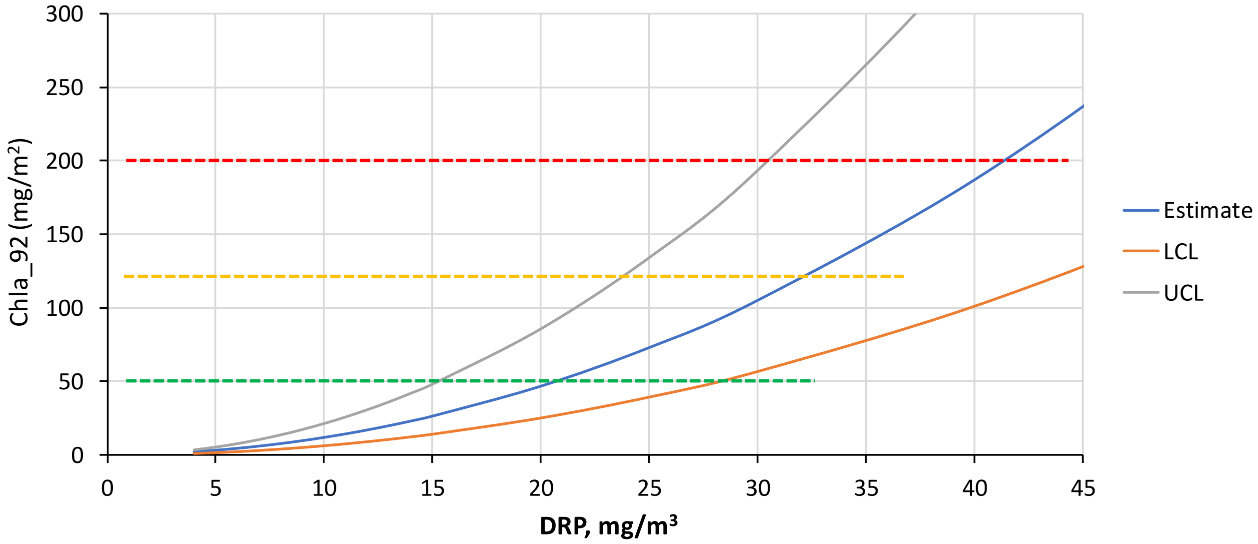
The combination of nneg > 250 and reversals > 130 was not observed, and no predictions were made under those scenarios.



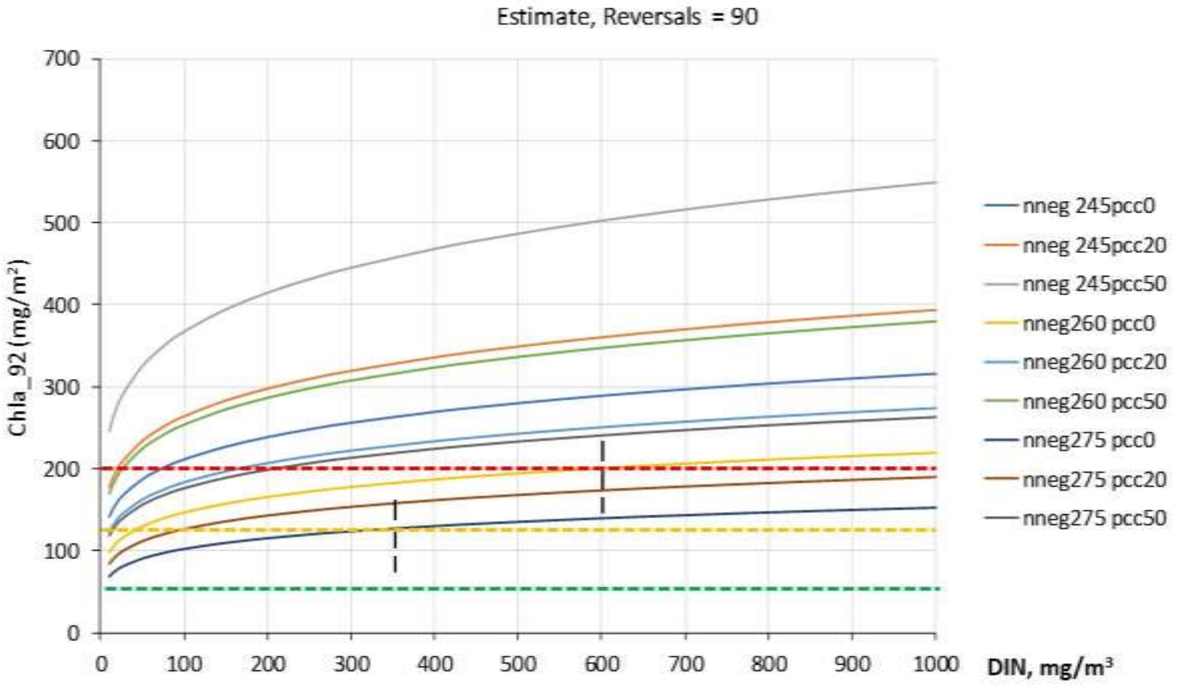


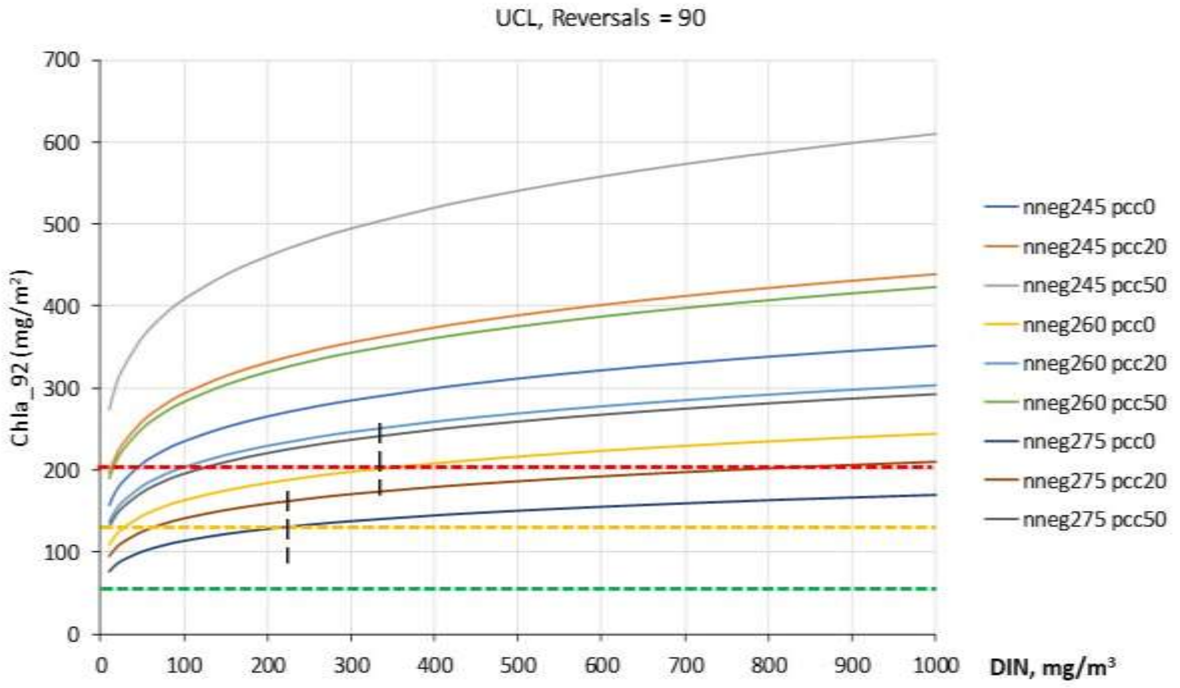
Model 12. Flow insensitive sites (DRP was the only predictor). The lower plot shows predictions for DRP < 45 mg/m³ to show the threshold values more clearly.

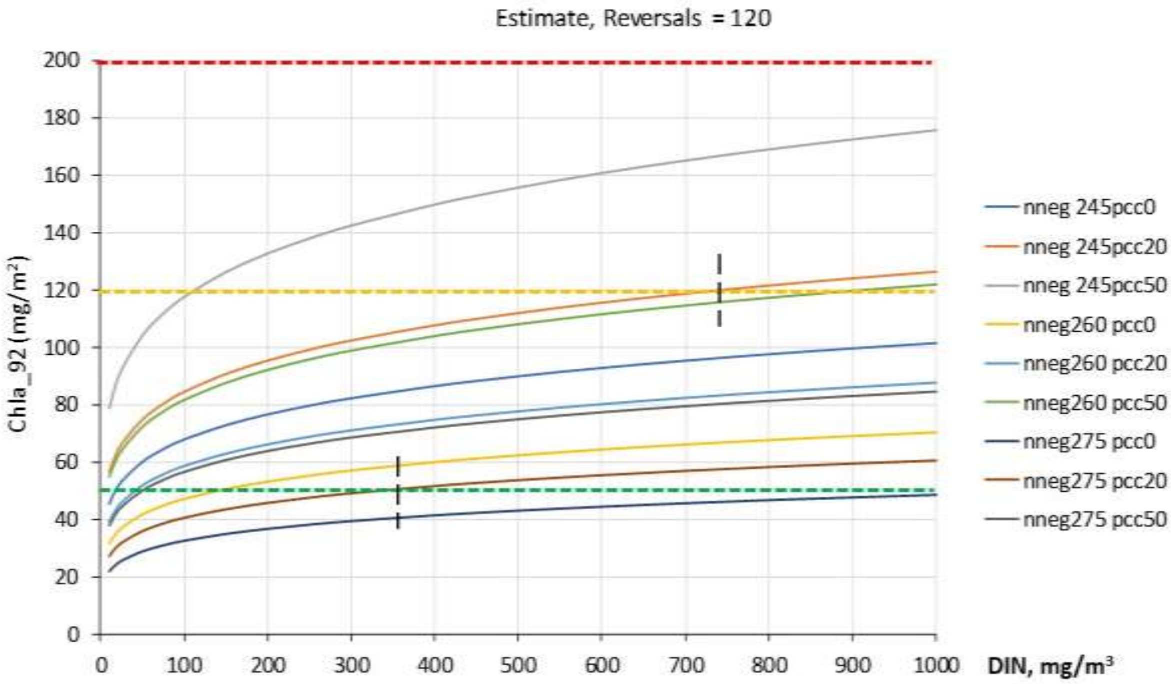




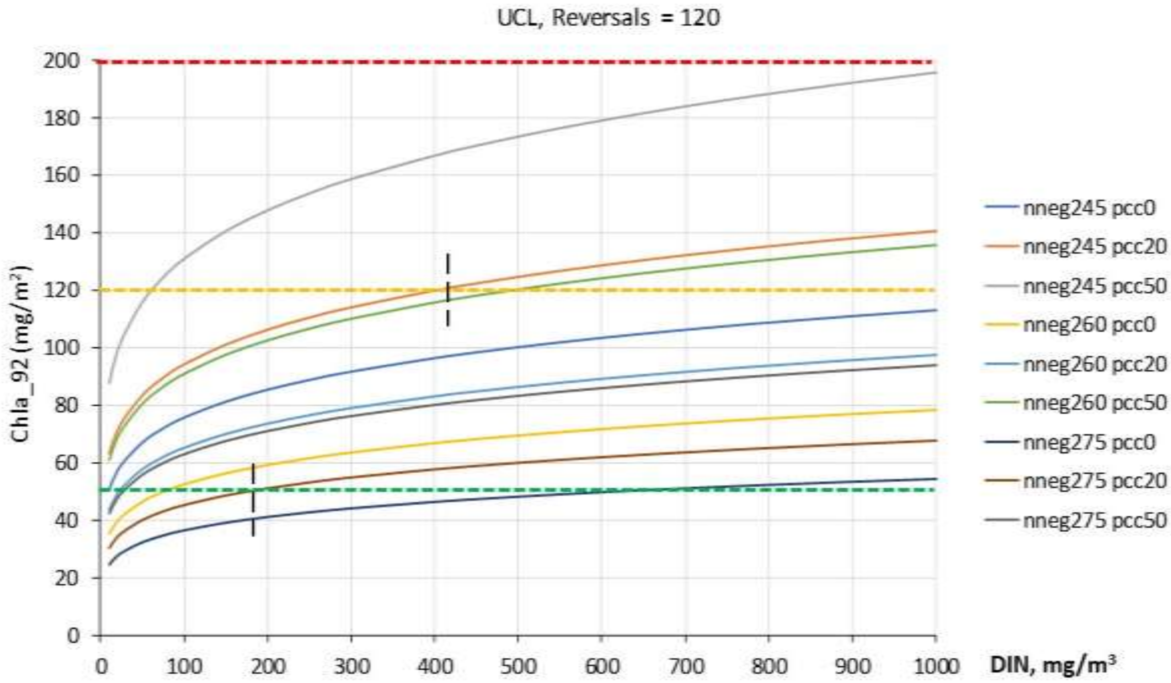
Model 25a. Flow-sensitive, lowland sites, DIN as nutrient predictor: three plots, one each for Reversals = 90, 120 and 150 /year





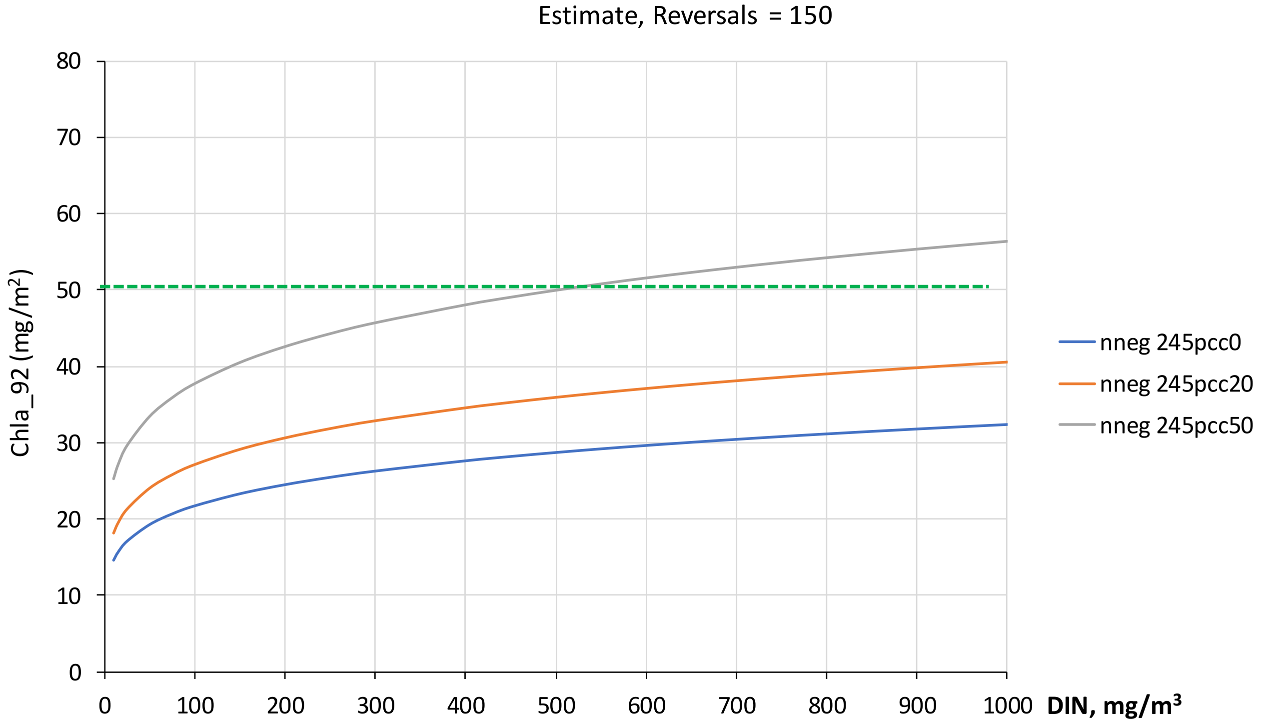


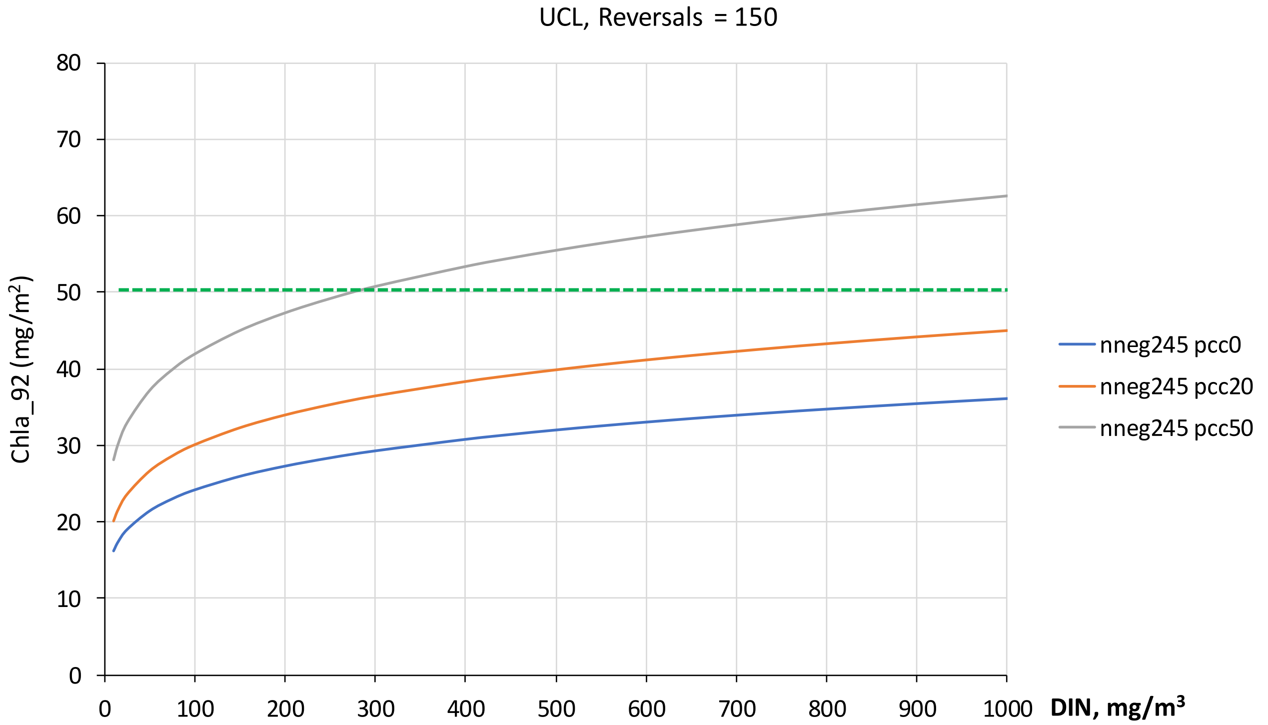
Estimate, Reversals = 120
200
180
160
140
120
100
80
60
40
20
0
Chla_92 (mg/m²)
0
100
200
300
400
500
600
700
800
900
1000
DIN, mg/m³
nneg 245pcc0
nneg 245pcc20
nneg 245pcc50
nneg260 pcc0
nneg260 pcc20
nneg260 pcc50
nneg275 pcc0
nneg275 pcc20
nneg275 pcc50



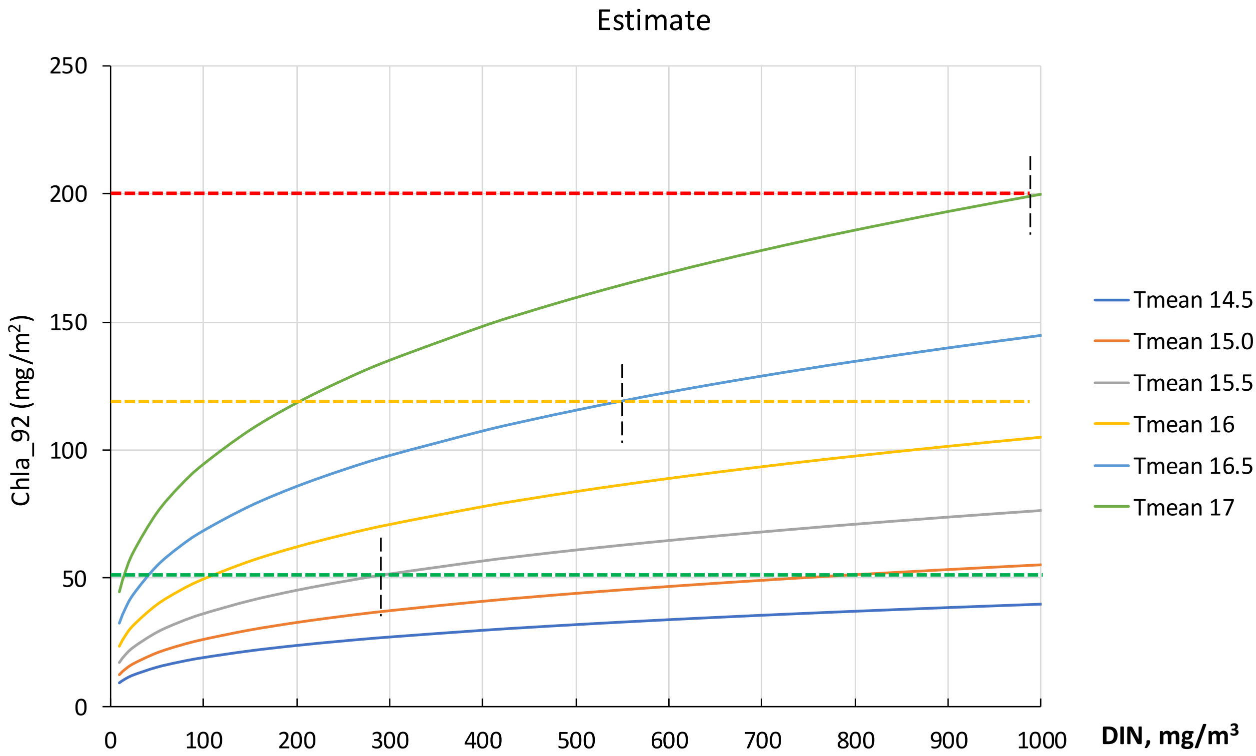
UCL, Reversals = 120
200
180
160
140
120
100
80
60
40
20
0
Chla_92 (mg/m²)
0
100
200
300
400
500
600
700
800
900
1000
DIN, mg/m³
nneg245 pcc0
nneg245 pcc20
nneg245 pcc50
nneg260 pcc0
nneg260 pcc20
nneg260 pcc50
nneg275 pcc0
nneg275 pcc20
nneg275 pcc50

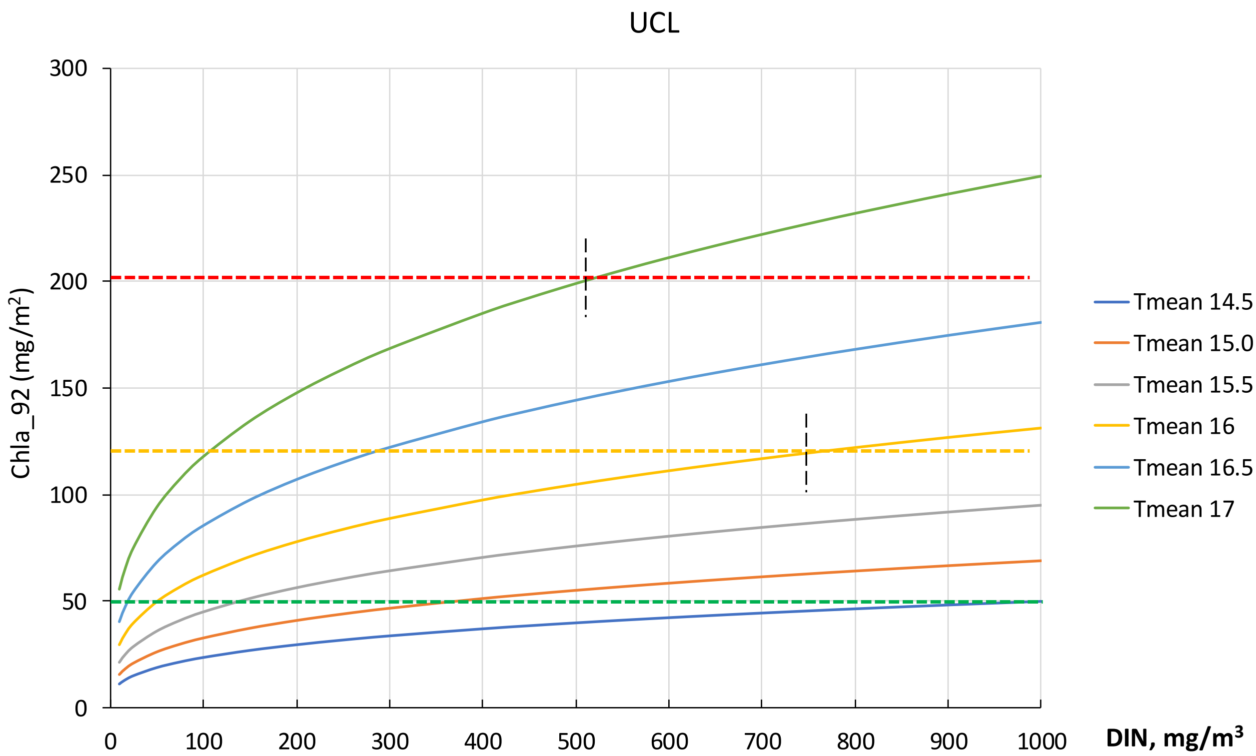
The combination of nneg > 250 and reversals > 130 was not observed, and no predictions were made under those scenarios.





Model 16. Sites classified in the REC with HS upstream geology: predictors DIN and Tmean.





Appendix E Distributions of available predictor variables

Note that transformed values (as specified in Table 5-1) are shown because untransformed data results in highly skewed histograms for some variables.