Limiting nutrients for controlling undesirable periphyton growth

NIWA Client Report: HAM2007-006
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Prepared for

Horizons Regional Council

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Executive Summary

Hawke's Bay and Horizons Regional Councils have sought advice on a number of questions concerning the management of nutrients (viz. nitrogen, N, and phosphorus, P) in order to minimise the occurrence of unwanted periphyton blooms. A key question asked was "if one nutrient element has been identified as limiting, do we need to manage the other?" A workshop was convened in Palmerston North on 25 October 2006, with an expert panel addressing a series of questions posed by the two Regional Councils. Key outcomes were as follows:

- Not all rivers and streams will require nutrient management to minimise unwanted periphyton blooms. Those with soft substrates, not discharging to lentic systems and with low macrophyte cover are largely exempt from nutrient management. All others need some form of nutrient management.

- Although nutrient management is not necessary to control periphyton growth in soft-bottom streams, it is still a sound strategy for (1) reducing inputs to sediments that might otherwise stimulate unwanted macrophyte growth, (2) managing downstream (hard-substrate) waters that might be subject to periphyton blooms and (3) avoiding eutrophication problems in downstream environments such as lakes, estuaries and coastal waters.

- Nutrient management is important for coastal waters and estuaries, where macroalgae and phytoplankton may be more of a problem than periphyton. Thus, it would be prudent to derive or use standards that prevent periphyton blooms in rivers that also provide adequate protection for estuarine and coastal waters.

- <u>Both N and P</u> need to be managed because of the interconnectivity of waterways (where different nutrients might be limiting in the same stream network).

- Periphyton growth and vigour is determined by antecedent water quality. This affects periphyton recovery from major disturbance events (floods). Lengthy exposure to high concentrations of nutrients is likely to give rise to a vigorous growth of periphyton that will respond more quickly than if it had grown in low-nutrient waters. For this reason, year-round control of <u>both</u> N and P is important.

- The most rigorous method for assessing periphyton response to nutrients is to conduct nutrient diffusing substrate (NDS) assays, but the soluble N:P ratio offers a useful tool for exploring the potential for one nutrient to be identified as limiting growth and to predict the likelihood of periphyton blooms.

- Other means for assessing the risk of periphyton blooms include: ratios of PC/PN (or %PN) and PC/PP (or %PP) of algal biomass, but care needs to be taken to avoid confounding results caused by entrained particulate material within the periphyton matrix biasing the PN/PC and P/C ratios. Bioassays can also be used to investigate nutrient limitation and are generally considered the "gold standard" against which other methods are assessed.

- It is important to carry out N:P calculations or NDS methods down a catchment with sites selected in relation to inflows, land use and point sources. If these are not known about 3-4 sites should be selected.

- As a general rule, a reduction in concentration of a given limiting nutrient will reduce periphyton biomass. There are few reported observations of this happening for diffuse source inputs of nutrients but there is supporting literature where point source inputs have been reduced.

- Applying controls only to the "limiting" nutrient (and not the other nutrient) is not recommended. Nutrient limitation for unwanted algae growth may vary spatially (e.g., estuaries versus upland rivers) and temporally (i.e., seasonally). Where there is a key indication of a single, limiting nutrient (e.g., P), it would be sensible to focus on managing that nutrient without neglecting controls on the other macronutrient (e.g., N).

- Permitting a land use because it is mainly known for being the source of one (non-limiting) nutrient, rather than the targeted limiting nutrient, may unwittingly allow other forms of pollution (e.g., faecal matter and sediment) to occur.

- Algal growth that is near-replete or near-balanced will not respond to enrichment with the limiting nutrient to the degree that severely-limited algae or severely-imbalanced growth will.

- With regard to periphyton response to the rate of nutrient supply: algae in fast-flowing, nutrient-poor water can grow as fast as algae in slow-flowing, nutrient-rich water.

1. Introduction

Hawke's Bay Regional Council and Horizons Regional Council are seeking recommendations on key water quality management questions relating to periphyton growth and limiting nutrients. Horizons has divided its Region into 44 Water Management Zones and 117 Water Management sub-zones. Monitoring has identified that excessive periphyton growth occurred or was likely to occur in a number of these zones. Further studies have shown the nitrogen loadings in the rivers originated predominantly from diffuse pollution, while phosphorus came from both point sources and non-point (diffuse) sources.

A Nutrient Diffusing Substrate (NDS) study carried out by Horizons on the Rangitikei River two summers ago showed that N was the limiting nutrient at the time of the study. As a result, Horizons has sought guidance on the need to control input of both nutrients to the River. It was outlined during the workshop that this question had very practical and far-reaching consequences, as managing either N or P rather than both is at the same time easier and less expensive for the regional Council, the farming community and the consent holders for discharges to the river.

There is presently a DRP[1] standard for the Manawatu Catchment (0.015 mg/m^3) but no Nitrogen Standard, and no nutrient standard for the rest of the Horizons Region. Horizons is currently in the process of defining a new management regime, including water quality standards relating to the values associated with the Region's rivers and lakes. As a consequence, Horizons is seeking guidance on the relevance of setting standards for either or both N and P to control nuisance periphyton growth, and at what river flows and time of the year these standards should apply.

The Regional Councils need to gain enough confidence that the set target (in terms of nutrient selected, and the degree of control) can deliver adequate control of periphyton maximum biomass before committing resource and effort towards managing one nutrient to the exclusion of the other. To investigate this further the two Councils have used the Envirolink fund to convene a workshop at Horizons Regional Council, Palmerston North, 20 October 2006, to address this topic. A key expectation of the workshop was to determine if there were situations where controlling just one nutrient (N or P) would provide adequate control of undesirable periphyton growth and, as a corollary, could you have unlimited inputs of the non-limiting element without compromising stream values?

[1] DRP = dissolved reactive phosphorus, also called soluble reactive P (SRP), or filterable reactive P (FRP).

Attending the workshop were:

Oliver Ausseil, Jon Roygard, Maree Clark, Kate McArthur (Horizons Regional Council)

John Phillips (Hawke's Bay Regional Council)

Russell Death (Massey University)

Barry Biggs, Chris Hickey, Scott Larned, John Quinn and Bob Wilcock (NIWA)

1.1 Background information on periphyton growth

Excessive periphyton growth on riverbed substrate is a common issue that affects a number of river values, including: Life-Supporting Capacity (LSC), Contact Recreation (CR), Aesthetics (Ae) and Trout Fishery (TF). The New Zealand Periphyton Guidelines (Biggs 2000) provide some guidance on the acceptable levels of periphyton biomass in relation to protecting different river values and uses. The procedure used by Horizons Regional Council for state-of-the-environment reporting is detailed in Appendix 1.

Excessive peak periphyton biomass is dependent on extended periods of stable or low flow, and on the absence of shade from riparian vegetation and low turbidity. Once these conditions are met, the rate of development and peak biomass is most strongly controlled by concentrations of bioavailable N and P in the water (Biggs 1996). For freshwaters it is common to regard bioavailable N as being the sum of nitrate+nitrite N (NO_X-N) and ammonia N (NH_4-N), while bioavailable P is taken as being DRP. Both elements are needed for periphyton growth, in an average mole ratio of 16:1, or 7:1 (N:P) by weight, as defined by the Redfield equations (below) (from Stumm & Morgan 1996).

$$106\,CO_2 + 16\,NO_3^{-} + HPO_4^{2-} + 122\,H_2O + 18\,H^{+} \rightleftharpoons \{C_{106}H_{263}O_{110}N_{16}P\} + 138O_2$$

$$106\,CO_2 + 16\,NH_4^{+} + HPO_4^{2-} + 106\,H_2O \rightleftharpoons \{C_{106}H_{263}O_{110}N_{16}P\} + 106O_2 + 14\,H^{+}$$

Thus, because both elements are essential it is theoretically possible to limit periphyton growth by focusing on controlling the element in shortest supply, viz. the limiting element. It should be noted, however, that the Redfield ratios are averages that are subject to change depending on future levels of nutrient availability and competition amongst species (Klausmeier et al. 2004). At moderate to low growth-limiting nutrient concentrations, high densities of invertebrate grazers can also retard the rate of accrual of periphyton biomass and may, in some situations, prevent the development of proliferation conditions (Biggs 1996).

The physiological process by which nutrients limit periphyton biomass accrual is important to understand when attempting to define and justify limits on daily nutrient loads. Whole mat nutrient limitation consists of two components (Bothwell 1989):

1. Specific growth rate limitation - this at the cellular level (μm-mm) and is particularly relevant to the cells growing on the outer boundary of mats. In turbulent flow, cell-specific growth is usually not limited unless macro-nutrient concentrations are very low (depending on periphyton species, these values might need to be <1 mg/m^3 (part per billion, or ppb) of, say, DRP.

2. Mat growth limitation - this occurs at larger spatial scales (mm-cm). As mats develop and thicken, diffusion resistance within mats increases. If nutrients cannot diffuse to the base of a mat, the attachment cells will die and the mat will slough. Thus, the thickness of the mat (i.e., overall biomass of a stream reach) is related to ambient limiting nutrient concentration. Concentrations which might limit mat growth and persistence are in the range of 10 – 15 mg/m^3 DRP.

In general, 'mat-limitation' should be the focus of management. In principle, managing the input of the limiting element should under certain conditions be sufficient to limit periphyton biomass in rivers to acceptable levels. This has significant implications for catchment management because it is likely to be cheaper and easier to manage one nutrient element, and not both macronutrients. A further consideration is that specific nutrient criteria need to be set within the context of the catchment hydrological regime. In catchments that flood regularly, less stringent nutrient criteria might be permissible because flood events will usually arrive frequently enough to prevent problem growths developing and the probability of these events in any given year then becomes an important part of the decision criteria. This is the essence of the statistical model of peak periphyton biomass developed by Biggs (2000a) and used in the New Zealand Periphyton Guidelines (Biggs 2000b). Snelder et al. (2005) showed how this model could be used to develop regional nutrient criteria within the context of variable hydrological regimes and a similar approach will be recommended in the current study. As far as we are aware, this is the first time that an attempt has been made in practice to draft regional scale nutrient guidelines in such a holistic way.

2. Nutrient Limitation Workshop

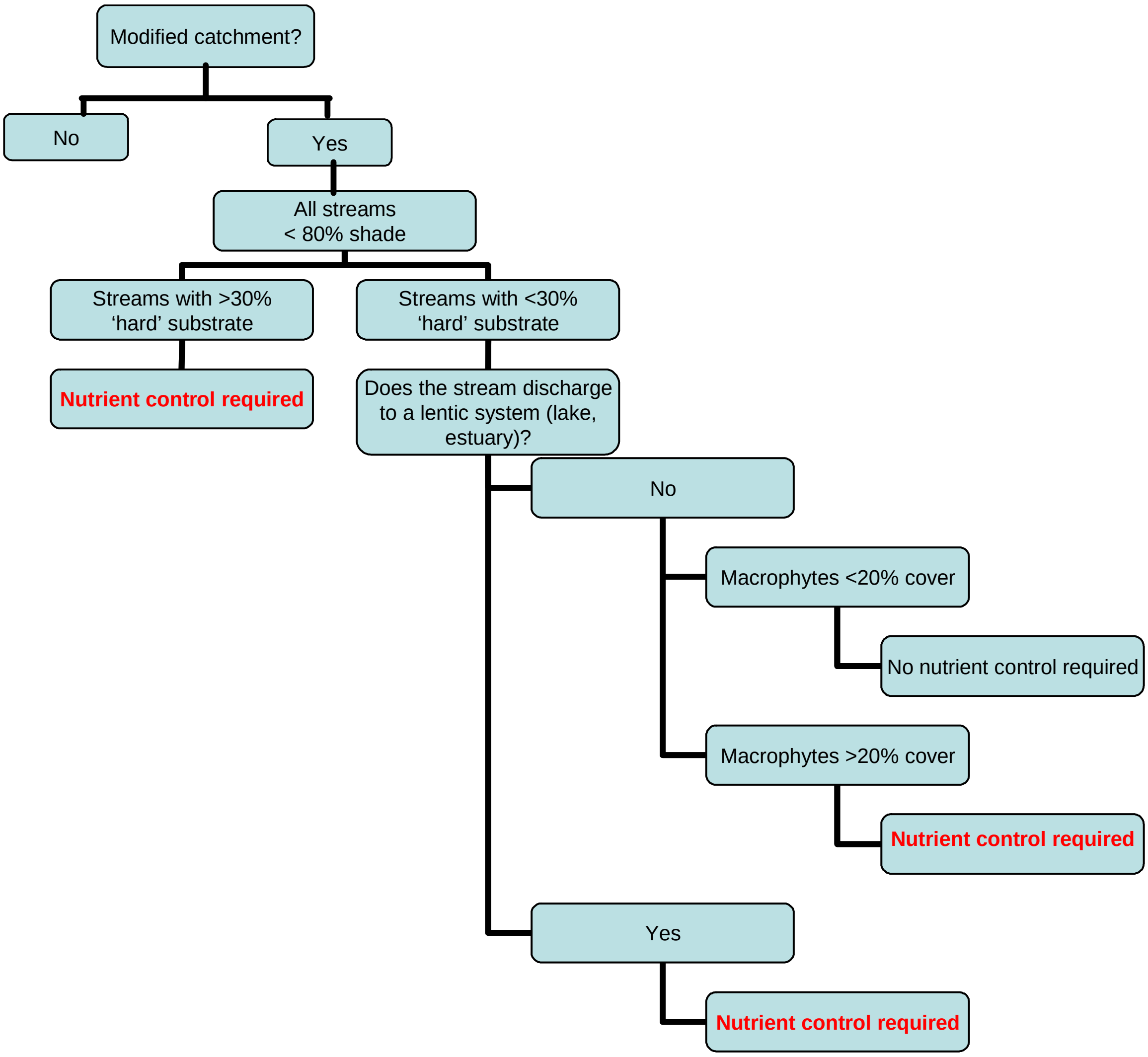
The workshop discussion focused on 12 pre-circulated questions compiled by John Phillips and Olivier Ausseil. The following sections list each of the questions and the ensuing discussions, concluding with consensus summaries and recommendations.

2.1 *Question 1:* Do all rivers need nutrient management? There can be situations where nutrients are not the factor limiting periphyton growth. Examples include shading in small streams or soft substrate and/or turbidity in large rivers.

2.1.1 What recommendations can be made on how to determine these areas, and what general rules can be made with regard to turbidity, stream width etc?

<u>Answer:</u>

Not all streams and rivers will require nutrient management. A simple decision rule that might be used to guide the spatial context for criteria development is as follows:



NB: streams that are highly shaded (e.g. 80%) and flow into nutrient-sensitive lakes and estuaries may act as conduits for nutrients because they are not taken up in-stream.

Commentary

Natural soft-bottomed streams (e.g., wetland streams in South Westland) may not require nutrient criteria for reducing algal growth in-stream. However, if streams drain into lentic or semi-lentic environments such as lakes or estuaries, where other eutrophication could occur, then nutrient criteria (in the form of 'total loadings') may be required. Also, soft-bottomed streams that are affected by human-caused sedimentation and bank failure may need riparian management measures that also reduce nutrient loading. Macrophytes in lowland streams are generally not limited by nutrient supply in the water column because their primary mode of uptake is from sediments, and these are usually sufficiently enriched. Macrophyte growth is most commonly limited by available light (Chambers & Kalff 1987), but this does not obviate the need for nutrient management as high water-column nutrient concentrations will enrich sediment nutrient pools (Carr et al. 1997). There are relatively few soft-bottomed streams in the Horizons and Hawke's Bay regions.

Light is a primary controller of periphyton growth, so shade and turbidity effects on light reaching the streambed moderate the influence of nutrients. Shade controls how much light reaches the streambed and the quality of that light. The rate at which light (specifically photosynthetically active radiation, PAR) is attenuated as it penetrates the water column (characterised by the coefficient, K_d, m^{-1}) is determined by turbidity and background water organic matter. This coefficient multiplied by the depth determines how much light reaches the streambed. Davies-Colley et al. (1992) derived the following relationship for brown-water streams of the West Coast:

$$\log K_d = -0.048 + 0.34\log\{\text{Turbidity}\} + 0.65\{\log g_{440}\} \quad (r = 0.92)$$

In a group of West Coast streams, with mean depth of 0.3 m, daily mean PAR at the bed at sites downstream of clay discharges was as low as 78 $\mu E\ m^{-2}\ s^{-1}$ (from an upstream mean of 336 $\mu E\ m^{-2}\ s^{-1}$) when turbidity downstream was 161 nephelometric turbidity units (NTU). Periphyton biomass was lower below all clay discharges that increased mean turbidity from 7 to 150 NTU. The discharges reduced periphyton primary production and phototrophic content (i.e., invertebrate food quality) and invertebrate abundance was lower downstream (Quinn et al. 1992).

Turbidity also influences the aesthetic effect of periphyton, since blooms may be less visible in turbid streams (although turbid streams in themselves may be considered unattractive). Effects of turbidity on both periphyton growth and aesthetic effects increase with depth for a given turbidity level. For example, once the turbidity is > 10-20 NTU the bed becomes invisible at a depth of 1 m and at 100 NTU the bed is invisible at 0.1 m depth.

Logging studies have shown the importance of shade/lighting on periphyton biomass. In the Coromandel Peninsula, periphyton proliferations were observed at clear-cut sites whereas biomass increases were low where riparian buffers were maintained such that stream DIFN was <20% (Boothroyd et al. 2004). DIFN is defined as the light received at a (partially shaded) site as a proportion of incident light (i.e., received at an open site) (Davies-Colley & Payne 1998). Another study (Davies-Colley & Quinn 1998) demonstrated a general increase in periphyton biomass with lighting in summer in North Island streams, but regional differences were observed in levels associated with periphyton chlorophyll *a* (Chl*a*) above the previous aesthetic nuisance guideline (100-150 mg Chl*a* m^{-2}). From these and experimental stream study results, it seems lighting needs to be less than 10-20% of open-cover levels to *prevent* blooms in shallow streams where other conditions are favourable, although DIFN <40% open may reduce the risk of blooms. In Toenepi it was found that 90% shade was needed to control the emergent willow weed (however, the native shade-tolerant species *Nitella hookeri* grew at this level). Davies-Colley and Quinn (1998) report that once the channel width is >8-10 m riparian forest struggles to exert enough shading to control periphyton.

Invertebrate grazers can also exert "top-down" control of periphyton biomass, so that high levels of periphyton *productivity* are transferred into biomass of stream animals (invertebrates and their predators, such as fish, birds and spiders) so that high periphyton biomass does not occur. In New Zealand, Welch et al. (1992) found that densities of over 3000 macro-grazers/m^2 were associated with low periphyton biomass despite elevated nutrient levels below some sewage discharges. However, flow disturbances and stressors that reduce invertebrate grazer numbers or activity (e.g., high temperatures) often release periphyton from this grazer control (Rutherford et al. 2000). Strong grazer control of periphyton is most likely to occur in streams that lack frequent bed-disturbing flows and have good instream habitat (e.g., low levels of sedimentation, good water quality, cool temperatures, and suitable riparian forest for insect life history completion).

The duration of high maximum biomass in streams is also a function of nutrient concentrations. High biomasses remain for longer under enriched conditions (Biggs 2000a). Therefore, while in some areas it may not be possible to reduce the nutrient concentrations to levels that totally prevent blooms; there may be beneficial reductions in the duration of high biomass.

The magnitude of biomass development during prolonged periods of low flow is also a function of local reach velocities. Where nutrient concentrations are moderate to high, low velocities (i.e., < ~0.3m/s) allow the development of high biomasses of periphyton dominated by filamentous green algae (FGA); moderate velocities (i.e., 0.3 – 0.7m/s) generally restrict FGA development and communities are more commonly dominated by sessile diatoms and short filamentous algae; and areas with high velocities (i.e., > 0.7m/s) are dominated by adnate diatoms and prostrate filamentous cyanobacteria (Biggs et al. 1998). Thus, while nutrient management is a primary opportunity to reduce both the magnitude and duration of maximum biomass, this should not be uncoupled from flow management whereby base-flow velocities are considered.

Summary and recommendations

- Although nutrient management is not necessary to control periphyton growth in soft-bottom streams, it is still a sound strategy for (1) reducing inputs to sediments that might otherwise stimulate unwanted macrophyte growth, (2) managing downstream (hard-substrate) waters that might be subject to periphyton blooms and (3) avoiding eutrophication problems in downstream environments such as lakes, estuarine and coastal waters.

- Riparian shade producing DIFN below 10-20% is needed to control periphyton growth in clear shallow streams, but

- The maximum channel width for effective riparian shading is about 8-10 m.

- Turbidity can effectively manage periphyton growth by limiting the quantity of light reaching the bed (i.e., acting like shade). This effect is greater in deep than shallow rivers. [However, note that if a large proportion of the suspensoids are mica minerals (such as occurs in many South Island streams) then high turbidity may not control productivity due to the reflective properties of mica.] High sediment loads in flood flows can “sand-blast” periphyton. Suspensoid levels may also need to be managed for the protection of instream values.

- Turbidity also hides periphyton. Stream bed periphyton at depths of 0.1 and 1 m cannot be seen when turbidities are above 10-20 NTU and 100 NTU, respectively.

- Efforts to improve stream habitat for invertebrate grazers are likely to reduce the incidence/frequency of nuisance periphyton blooms by enhancing “top-down” grazer control. Shading to control stream temperature, as well as limiting plant growth, will be particularly effective (Quinn et al. 1994).

- Reducing both N and P may reduce the duration of peak periphyton biomass. Thus, year-round nutrient control is needed.

Follow up suggestions:

Analyse Horizons’ current periphyton data against corresponding flow and nutrient measurements in order to see if any obvious relationships are apparent.

Develop a black disk – turbidity relationship for Manawatu and Hawke’s Bay rivers using Regional Council and National River Water Quality Network (NRWQN) data.

Decide on typical stream depths and develop a table relating visibility of bed in relation to depth for various states (e.g., flow).

Collate or measure K_d values for these rivers in relation to a range of turbidities and flows.

2.1.2 If there are likely to be effects on downstream water quality (e.g. lakes, larger rivers, estuaries and sea) are there stream reaches that can be exempt of nutrient management strategies (including, e.g., resource consent conditions or rules on farm nutrient management)?

Answer:

No.

Commentary:

It is probably impractical to develop a patchwork of streams or reaches that are subject to or exempt from nutrient management and it may be simpler therefore to apply nutrient criteria and management requirements uniformly unless there are clearly no downstream periphyton or macrophyte issues (see decision tree above). Also, it is known that individual alga species have specific (different) responses to N and P.

Downstream lakes and enclosed estuaries need specific consideration that takes into account characteristics, such as flushing, extent of shallow and inter-tidal areas, and previous history of eutrophication and occurrence of nuisance plants. It is likely that nutrient limitation in marine waters of both Regions will be limited to estuaries and coastal waters close to river mouths, because of the high degree of mixing/dilution with the respective coastal waters. In this case, macroalgae (e.g., *Ulva*) are the main problem plants rather than periphyton, but nutrient-biomass relationships are not well understood for macroalgae.

Summary and recommendations

- Nutrient management is important where there are sensitive downstream waters, but probably not so much for managing periphyton as for macro-algae and phytoplankton growth.

- Setting standards for avoiding algal blooms in estuaries and coastal waters will require specific case studies because of the local conditions (mixing of waters etc.). A precautionary measure would be to set freshwater nutrient controls that also adequately protect coastal and estuarine waters.

2.2 *Question 2:* What is the best method e.g., nutrient diffusing substrates (NDS) and N:P ratio?for determining the limiting nutrient,

2.2.1 What practical recommendations can be made, including detailed calculation methods (N:P ratio: dependence on flow and seasonality, conditions under which it can be used), and field methods (NDS: deployed what time of year? For how long? More than one year?)

Answer:

Using the soluble N:P ratio during the summer “growth” season is a pragmatic approach, but you need to have a sufficient number of samples covering a range of flows. This approach should be benchmarked against nutrient diffusing substrate data for the sites and against observed periphyton blooms. In addition, there is a need to view N:P ratios in the context of the absolute N and P *concentrations*. If both are well above levels that would be expected to saturate periphyton growth, the ratio is of much less relevance. Similarly, at low nutrient concentrations where there is unlikely to be a periphyton nuisance the ratio approach may also be irrelevant. See Biggs (2000a) for a discussion of approaches for determining limiting nutrients.

Commentary:

When determining soluble nutrient concentrations in streams, it is really important that sterile procedures are followed and that at least 2 replicates are collected as contamination (particularly of ammonia and phosphorus) is an ever-present issue. With concentrations of some nutrients being so low, extreme errors can easily be generated once ratios are calculated (e.g., minor contamination could result in DRP changing from 1 to 2, resulting in an N:P ratio of 20:2 rather than 20:1 with a reliable DIN concentration of 20 ppb. This would lead to an opposite conclusion compared with reality).

It may be worthwhile examining the periphyton (particulate nutrient concentration) PN:PC ratio and PP:PC ratio for cellular evidence that the algae are running out of N or P as done previously in NZ stream surveys (e.g., Biggs and Close 1989, Biggs 1995). In experimental stream studies at Whatawhata, low tissue PN:PC ratios (<0.08, equivalent to < half the optimal Redfield Ratio, classed as extreme N limitation by Healey, 1985) were found when the DIN dropped below 100 ppb in late summer (Quinn et al. 1997). The DIN:DRP at this time (about 2:1) also indicated N limitation, whereas it was from 8:1 to 30:1 earlier in the spring and summer. In short, an integrated assessment is likely to be necessary to accurately deduce what is limiting at different times of the year. However, it should be noted that cellular nutrient content and biomass growth are often uncoupled. Furthermore, different algal taxa and assemblages have different nutrient storage capacities, and different physiological requirements. Both ambient and tissue nutrient ratios become less accurate indicators of nutrient limitation as periphyton mats mature.

In theory, direct identification of limiting nutrients with assay (enrichment) experiments is more accurate than ratios in ambient water samples (e.g., DIN:DRP, TN:TP, DIN:TP) or in algal tissues. Ambient ratios are unlikely to precisely match the requirements of individual algal species, or the aggregate assemblages. Algal assemblages track shifting nutrient environments in terms of growth and composition, but responses can lag way behind environmental changes because of internal storage mechanisms, recycling at the mat scale, etc. (see Francoeur et al. 1999 and Francoeur 2001 for a discussion on the different methods of determining in-situ nutrient limitation).

In general, ambient N:P ratios based on multiple samples collected throughout the year (e.g., monthly) are inexpensive, indicative, and most useful when they are highly skewed. For example, DIN:DRP ratios of 50:1 and 3:1 probably indicate P-limitation and N-limitation, respectively, unless concentrations of both DIN and DRP are well above levels expected to saturate growth. At other times experiments should be used to verify the limiting nutrient. N:P ratios in rivers, such as the Manawatu River (Appendix 2), vary between sites, seasonally and from year to year.

2.2.2 Importance of time scales, residence times, and frequency

<u>Commentary:</u>

Nutrient limitation assays that indicate co-limitation may actually reflect serial limitation by two nutrients. This occurs when growth supported by the initial limiting nutrient saturates, the limiting nutrient shifts, and growth in the combined treatment continues (Fig. 1). If the question is "What nutrient is limiting <u>at this point in time</u>?", then the experimental period should be minimized. Alternatively, the focus should be on the single-nutrient treatments

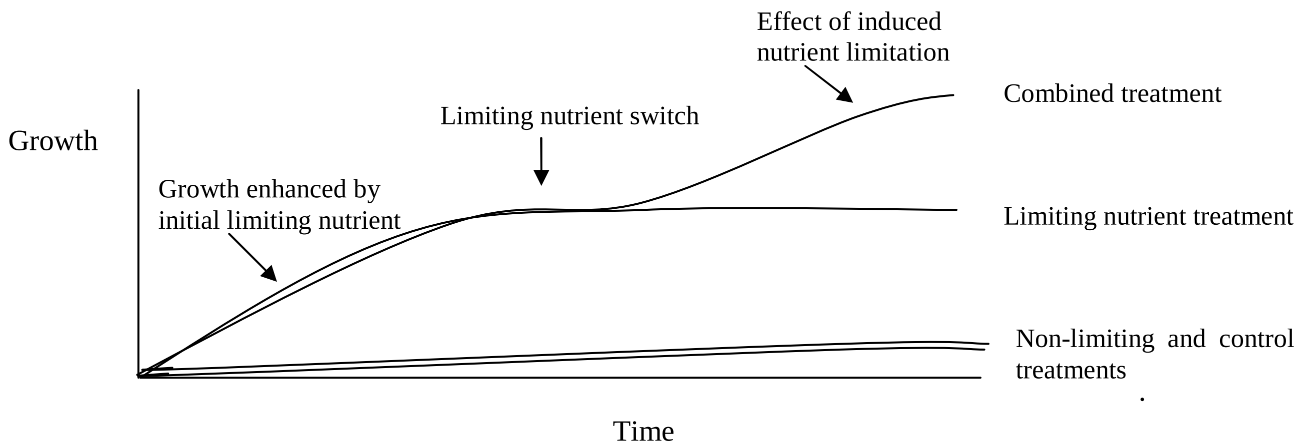


Figure 1: Example of the effect of a change in the limiting nutrient in a nutrient diffusing substrate experiment.

Some researchers in the United States advocate nutrient criteria for streams based on total (dissolved + particulate) concentrations and others on dissolved inorganic concentrations. However, particulate N and P must be dissolved and/or remineralized prior to becoming bio-available. So the particulate fractions of TN and TP are not usually available to the benthic algae at the sampling site. TN and TP are more relevant in lakes, where the particulate stock represents potential availability. Very slow streams should have relatively higher rates of remineralisation per unit length. In general, short residence times in small stream segments (scaled to algal samples) in New Zealand mean that DIN and DRP should be assessed.

Seasonal NDS assays are recommended initially, as the appropriate frequency to determine algal responses to long-term changes in nutrient concentrations and N:P ratios at different flow rates. If it is clear that there is no seasonal shift either in limiting nutrient identity or severity of limitation, go to biannual or annual frequency.

2.2.3 What spatial frequency is required for sampling within a catchment?

Answer:

It is important to do N:P calculations and/or NDS methods down a catchment system with sites selected in relation to river inflows, land use and point sources. If these are not known, about 3 or 4 sites could be selected. In the case of the Horizons Regional Council rivers, the catchment nodes that have been selected for assessing loads seem like sensible starting points.

Commentary:

Scott Larned and Marc Schallenberg hypothesise (unpublished communication) that switching between limiting nutrients (or co-limitation) is frequent in undisturbed catchments, both temporally and spatially. Spatial switching refers to changes in nutrient limitation among the aquatic ecosystems within a catchment (tributaries, rivers, wetlands and lakes).

Summary and recommendations

- The most rigorous method for assessing periphyton response to nutrients is to conduct NDS assays, but the soluble N:P ratio (see next bullet) offers a useful tool for exploring the potential for one nutrient to be identified as limiting growth and to predict the likelihood of periphyton blooms.

- Because periphyton respond to an integrated set of antecedent water quality conditions, it is useful to have year-round concentrations of soluble N and P (monthly frequency if possible) at a wide range of flows (this differs from the current DRP standard in the Manawatu Plan that only applies when river flows are at or below half median flow).

- Both N and P need to be managed because of the interconnectivity of waterways (where different nutrients might be limiting in the same stream network), and because of temporal changes in N:P ratios and in periphyton response.

- It would also be useful to know the extent of present periphyton blooms (especially biomass data) in relation to current N and P concentrations and to identify those catchments that are potentially capable of "flipping" to a eutrophic state.

- We recommend that the Regional Councils consider conducting regional risk assessments that take into account geology, stream lighting, climate, flow regimes and land use, as well as ambient water quality (see below). The objective of this would be to determine the natural levels of N and P (e.g., mudstone catchments may have naturally high P levels and thus tend to be N limited) and to understand the extent to which nutrient control is possible in each catchment.

2.3 *Question 3:* Are there alternative lower cost methods? (Alternatively, what metrics and methods are recommended for assessing the risk of periphyton blooms?)

2.3.1 Nutrient levels in algal biomass

Answer:

Ratios of PC/PN (or %PN) and PC/PP (or %PP) of algal biomass have been used to assess N and P limitation in a few NZ studies (see Quinn et al. 1997, Biggs 1995, and Freeman 1986). This can be problematic because of entrained particulate material within the periphyton matrix biasing the PN/PC and P/C ratios (Francouer et al. 1999). However, this can be managed to some extent by cleaning the periphyton of detritus before analysis (see Freeman 1986), but adds considerably to processing costs.

Bioassays can also be used to investigate nutrient limitation and are generally considered the "gold standard" against which other methods are assessed. A range of techniques from laboratory to field assays have been used that vary in degree of control and standardisation, and choice of methods involve trade-offs between control/replication, realism and cost. An example of a laboratory bioassay is that of Freeman (1986) who assessed cleaned *Cladophora* filaments from the Manawatu River for N limitation using the ammonium uptake rate (AUR) and P limitation using Alkaline Phosphatase Assay (APA). Recently, rapid fluorescence techniques have been developed as potential laboratory assays for nitrogen limitation in phytoplankton

(Holland et al. 2004). In future such methods may provide a more rapid method for assessing nutrient limitation, but we are not aware of examples of their application to periphyton assessment.

Nutrient diffusing substrates (NDS) are a field bioassay of biomass yield limitation by nutrients. These have the advantage of field realism, but can be more costly than laboratory bioassays if multiple site visits are needed for maintenance. Also, they are prone to equipment losses due to flow disturbance and debris accumulation.

2.4 *Question 4:* How much certitude do the methods above provide?

2.4.1 Can the conclusions (i.e., whether N or P is limiting) change seasonally, with flow, following a large flood, or during a long drought?

Answer:

Yes (see Appendix 2 fig. (e)). Flood events markedly alter the relative importance of point and non-point (diffuse) sources of pollution and hence, the relative supply of N and P. Knowledge of flow regimes is also important because the time between disturbance events dictates whether blooms of periphyton can occur for any given nutrient level. If a system is prone to floods and thus short accrual periods (on average) then the nutrient criteria could be higher than for more hydrologically stable systems (see Biggs 2000b). Similarly, depending on flow regimes and likelihood of periphyton blooms occurring, dividing the year up into summer and winter seasons might be considered for managing nutrients and associated periphyton growth. For example, if floods are very frequent over winter, but not summer, then nutrient criteria could be more relaxed over winter without increasing the probability of having a bloom because of hydrological control of biomass.

Commentary:

The FRE3 statistic – the number of floods per year that are larger than three times the median flow and more than one day apart – is a broadscale descriptor of the amount of biological disturbance occurring in the stream. It has been shown that as FRE3 increases the amount of algae in the stream decreases and this has implications for the uptake of nutrients from the water column. At some intermediate level of disturbance (FRE3 10 to 20), the number of invertebrate taxa and grazer invertebrate densities may reach a maximum. Events with large amounts of gravel movement, or mobile and abrasive fines, may remove or regulate periphyton mats (Clausen and Biggs 1997).

Winter floods tend to release high NO_3-N from improved pasture (Wilcock et al. 1999) with resulting high N:P ratios. In summer, nitrogen concentrations tend to be much lower in streams as a result of both lower inputs (greater uptake by terrestrial vegetation etc.) and greater uptake by the periphyton. On the other hand, summer low-flows often release P from sediments so that N:P ratios are low (see Appendix 2). At present the models linking nutrient concentrations with periphyton biomass accrual are based on average monthly nutrient concentrations based on data collected for more than a year (Biggs 2000a), however it might be possible to redefine these relationships to just consider the summer 'season' if flow regimes are also very seasonal.

2.4.2 Will a reduction in limiting nutrient concentration allow a reduction in periphyton biomass (all other things being equal)?

Answer:

Although there are examples of point source nutrient inputs causing increases in periphyton biomass (e.g., Welch et al. 1992) and growth rates, there are few counter examples that show reductions in biomass or growth rates in response to managed nutrient reductions. However, there is no theoretical reason why a reduction in nutrients should not be effective in reducing both the magnitude and duration of periphyton blooms.

Commentary:

The Bow River (Canada) study provides one well-documented case study where the *downstream extent* of nuisance periphyton biomass was reduced by control of wastewater nutrient loading. The biomass of periphyton and aquatic macrophytes (*Potamogeton vaginatus* and *Potamogeton pectinatus*) in the Bow River was sampled over 16 years to assess the response of these plants to improved phosphorus (1982-1983) and nitrogen removal (1987-1990) at Calgary's two municipal wastewater treatment plants. These improvements in treatment reduced total phosphorus loading to the Bow River by 80%, total ammonia loading by 53%, and nitrite + nitrate loading by 50%. No change in periphytic biomass was detected after enhanced phosphorus removal where total dissolved phosphorus (TDP) in river water remained relatively high (10-33 mg/m^3). However, periphytic biomass declined at sites further downstream with TDP <10 mg/m^3. Regression analysis predicted that nuisance periphyton biomass (>150 mg m^{-2}) occurred at TDP > 6.4 µg L^{-1} (95% confidence interval: 1.9-7.6 mg/m^3). Macrophyte biomass was inversely correlated with river discharge and was lower during high-discharge years. Biomass also declined following enhanced nutrient removal, with the greatest decrease following reduced nitrogen discharge. These results provide the first evidence for a response of periphyton and aquatic macrophytes to enhanced nutrient removal from municipal wastewater (Sosiak 2002).

There are delays in time between nutrient conditions at a given moment and periphyton response: this will differ between systems depending on where they are. Responses are mostly non-linear and, as noted earlier, depend on hydraulic and other conditions as well as nutrient supply.

Streams could be categorised into classes of streams according to their differing sensitivities (see Periphyton Guideline for examples).

3. Catchment Management Implications

3.1 *Question 5:* **How does the current nutrient situation affect the results of a limiting nutrient study? Are there other factors to consider, e.g., natural factors, in making decisions about nutrients to target for management? (Please refer to the Manawatu example at the end of this list of questions)**

Answer:

Short-term blooms are “the norm” in many rivers, but as N and P inputs increase blooms become greater in biomass and longer in duration (Biggs 2000a). It might be worth taking a values-based approach whereby the Regional Councils would determine the extent to which (specific) waterbody periphyton criteria may be compromised, and then using water quality and hydrological data to determine exceedance frequencies (see Snelder et al. 2004 for an example of this type of approach).

Commentary:

In section **2.4.1** we refer to natural or “background” levels as well as to seasonally varying water quality from diffuse inputs from improved pasture. In considering nutrient loadings it might be best to make an integrated catchment assessment and derive total maximum daily loads.

3.2 *Question 6:* **What are the critical times and flows when nutrient inputs to waterways should be managed most intensively? Peak periphyton biomass is usually higher during periods of stable flow, usually prolonged periods of summer low flows. This makes direct input (i.e., discharges) during low flow an obvious target. How significant is nutrient input into a river during periods of limited periphyton growth (e.g., high flows, winter)? Storage in instream sediment and subsurface nutrient transfer during base-flow are possibly important considerations for this question. Will N- and P-limited systems have different answers?**

Answer:

See answers in Section 2.4 above.

Also, periphyton growth and vigour is determined by antecedent water quality. This affects periphyton recovery from major disturbance events (floods). Thus, lengthy exposure to high nutrient concentrations is likely to give rise to a vigorous growth of periphyton that will respond more quickly than if it had grown in low-nutrient waters. For this reason, year-round control of N and P is important.

Commentary:

Our opinion is that flood transported nutrient loads are less important than those at base-flow, but this will vary with the retention characteristics of the stream (i.e., its ability to trap sediments transported in floods that release dissolved nutrients to periphyton later when growth conditions are favourable) and how these change downstream. However, the influence of flood flows on base-flow nutrient supply is not well understood.

3.3 *Question 7:* If one nutrient (N or P) is found to be limiting at a catchment or sub-catchment scale, can the management be centred on only this nutrient? The direct resource management implications of this could be, in a say P limited catchment, to have no water quality standards, no resource consent conditions and no land use controls on the amount of N that can be discharged in the environment. (NB Ammonia-N would be limited for its direct toxic effects on aquatic life).

Answer:

A key question to be asked is "how do you determine what the limiting nutrient is" during growth periods if the N:P ratio is not obviously biased in one direction? This clearly depends on the technique that is used and would need to take into account temporal lags between water nutrient concentrations and periphyton growth response (also see Answers in Section 2).

Planning and implementation of nutrient controls should be based on an integrated catchment approach. A nutrient→ bloom model must be accepted to deal with a single nutrient response relationship. If multiple lines of evidence indicate extremely high levels of the other (non-limiting) nutrient then control is not justified. In practice this is seldom the case (year round) (e.g., see Francoeur et al. 1999), which means that both N and P should be controlled.

It is not wise to focus only on managing the limiting nutrient (as explained in the next section).

Commentary:

The risk of managing just one nutrient (N or P) in a reach or sub-catchment is that *downstream* waters may respond to the uncontrolled nutrient. Furthermore, a large background concentration of the non-limiting nutrient has a high potential to cause or contribute to a bloom if control on the limited nutrient fails (e.g., a particularly wet period following large scale superphosphate application may lead to much greater than usual amounts of P in waterways where there are no controls on catchment N inputs). Spatial variations in nutrient limitation may also make this strategy risky.

A recent UK report (Maberly et al. 2004) examines the importance of limiting N inputs in order to avoid freshwater eutrophication. The report concluded: "It is difficult to produce general, definitive statements about the types of habitat that are likely to be sensitive to N-enrichment. Nevertheless, it seems to be clear that in upland lakes, and probable streams and rivers, nitrogen is potentially a limiting factor. Most if not all lowland rivers in the UK probably have concentrations of nitrogen that exceed the requirements of the phytoplankton and macrophytes and probably also the periphyton. However, there is some recent evidence linking low macrophyte species richness to high concentrations of nitrate. If this is subsequently shown to be causal it will have a major impact on the need to regulate and reduce nitrogen concentrations. In lowland lakes, nitrogen limitation is most likely in lakes where the catchment is rich in P, where internal P loading from the lake sediments is high where lakes have a long water residence time and few inflows, where lakes are dominated by submerged macrophytes and where the lake inflows passes through wetlands prior to entering the lake. Despite these general conclusions it will be necessary to establish nitrogen-limitation, and hence sensitivity, on a site-by-site basis using one or more of the approaches outlined (in the report)."

Summary and recommendations

Restricting control to just one (limiting) nutrient is very risky and is not recommended. However, where there is a key indication of a single, limiting nutrient (e.g., P), it would be sensible to focus on managing that nutrient without removing controls on the other macronutrient (e.g., N).

3.4 *Question 8:* How is the decision about selecting the nutrient to target affected by:

3.4.1 How amenable that nutrient is to management and mitigation?

Answer:

This decision, if made at all (see comments above), should be based on scientific arguments and not on convenience or available technology (e.g., for P in point source discharges).

Commentary:

Effective management comes from a combination of focusing on the key things (i.e., limiting nutrient) and what can be most effectively managed. Nutrients can be dealt with either at source (e.g., by restricting application rates for fertilisers, avoiding direct input of fertiliser into waterways, managing grazing to avoid pugging, managing stock type and stocking rates) or along interception pathways (e.g., utilisation of wetlands for returning nitrate to the atmosphere as nitrogen gas, via denitrification) with a range of options possible (see Appendix 3). It would be prudent to allow for innovative new solutions for managing nutrient loads to waterways (McDowell et al. 2004).

3.4.2 Factors like possible land use change? As a consequence of this, should councils need to consider cropping and other land use potential in making such decisions?

Answer:

Yes, potential land uses and likely effects on water quality should be considered. For example, market gardening in the South Auckland area (Bombay Hills) causes streams to have very high N concentrations (10-20 g m^{-3} as NO_3-N) because of the fertiliser use and groundwater contamination. Likewise, other land uses can dramatically change catchment loads, e.g., cropping (sediment, N and P); dairying (N and faecal matter) (Wilcock & Nagels 2001, McDowell et al. 2004).

Commentary:

It is important therefore, that councils consider land use both from the standpoint of intensity of specific water quality variables, and utilise an integrated catchment approach to assessing potential water quality problems.

3.5 *Question 9:* **If the outcome of the above is that both nutrients need to be targeted for management, is this implemented equally from the outset, or is there a hierarchy/sequence of considerations over time and space in a particular catchment?**

Answer:

This could be done taking an adaptive management approach with a pre-determined hierarchy of control measures in a catchment based on predicted return (i.e., degree of reduction in N & P) for control measure effort. A useful approach might be to define a hierarchy of priority classes/levels (ranging from 'do-nothing' to a highly prescriptive response), and clearly outline a decision framework for making these priority choices within a catchment.

3.6 *Question 10:* **Should we perhaps consider a decision tree based on the ideal choice v. scenarios where certain land uses are allowed as of right? For example, should we allow intensive dairying with the knowledge that it is likely to increase N levels to some degree?**

Answer:

Given that both N and P should be managed, albeit with varying degrees of importance for controlling periphyton growth, we don't believe that it would be good judgement to permit land uses that are known to have high specific yields of a particular nutrient (e.g., dairying for N) while at same time prohibiting or tightly controlling land uses that have high yields of a targeted nutrient (e.g., hill-country sheep and beef for P) (Quinn & Stroud 2002; McDowell et al. 2004, Wilcock et al. 2006a). Indeed, it would be a rare situation that, for example, only N is affected by a land use intensification practice without also increasing P. Further, intensive land uses, like dairying, do not only release large amounts of N but also have high specific yields of faecal indicator bacteria (*E. coli*) and, in some cases, P (Wilcock et al. 2006a). Thus, permitting a land use because it is mainly known for being a source of one nutrient may unwittingly allow other forms of pollution to occur. In such cases it would be reasonable to promote best management practice for N management on farms, but have more targeted P management (including land use change management) to ensure P levels do not rise (Appendix 3).

Commentary:

Best management practices, including new innovative forms of treatment may be implemented that change the way particular land use loadings to waterways. Regional Councils will have to make difficult decisions based on available knowledge and a degree of trust in what particular industries and interested parties claim can be done, as well as ensuring that such BMPs are in place.

3.7 *Question 11:* Is it feasible (or indeed desirable) that different nutrients be targeted in different parts of one catchment?

Answer:

As noted above, we recommend that both N and P loads be considered for management. It is feasible and probably necessary to do this because pathways and predominance of inputs will vary with topography, land use etc. and therefore be spatially non-uniform.

From a consideration of periphyton blooms it would be necessary to firstly determine whether there are spatial changes in limiting nutrients within a given stream network. Secondly, it would be useful to know how likely is it that different stream reaches within catchments receive greatly different N and P loads from different land uses. This could be estimated from known export coefficients for land uses (Elliott et al. 2005) and knowledge of particular land use activities, such as fertiliser application regimes. Again, we recommend an integrated catchment approach to managing nutrients.

Commentary:

There are some situations where P can be naturally high because of catchment geology (e.g., preponderance of soft-Tertiary siltstones in the catchment), in which case P management might be impossible below certain levels. However, big periphyton blooms of long duration appear to occur most frequently with a combination of intensive landuse and natural enrichment (Biggs 1995) so it is still worthwhile invoking BMPs in siltstone catchments/sub-catchments (also see McDowell et al. 2004).

3.8 *Question 12:* How are decisions about freshwater environments integrated with those for marine environments? Is it universal that marine environments are N limited and hence that N should also be targeted universally for management in freshwater? Or is there a particular 'N load limit' that marine environments can cope with given that the N cycle may (or may not) provide an avenue for alternative N loss from marine environments?

Answer:

Coastal water concentrations of N and P are highly variable being influenced by the mixing of freshwaters and oceanic water. Open ocean water is nutrient deficient at the surface and nutrient concentration increases with depth. There is some doubt about whether N or P is limiting in these waters (e.g., Downing et al. 1999).

A review of the experimental and observational data used to infer P or N limitation of phytoplankton growth indicates that P limitation in freshwater environments can be demonstrated rigorously at several hierarchical levels of system complexity, from algal cultures to whole lakes. A similarly rigorous demonstration of N limitation has not been achieved for marine waters. Therefore, we conclude that the extent and severity of N limitation in the marine environment remain an open question (Heckey & Kilham 1988).

Coastal waters near the continental shelf around New Zealand have DIN:DRP ratios of $\leq$ 7, indicating N maybe somewhat limiting (DIN = NO_X-N + NH_4-N). Nearer the coast N:P ratios are very low (S. Pickmere, NIWA, pers. comm), further supporting the idea that near-shore waters are depleted in N with respect to P.

Summary and recommendations

Because of the dynamic nature of coastal waters for the Horizons and Hawke's Bay Regions (i.e., open, high energy, coasts with rapid mixing of freshwater inputs) the issue of nutrient enrichment and algal blooms caused by land-water interactions should be confined to estuaries and poorly mixed embayments. Macroalgae (e.g., *Ulva* sp.) are the main problem plants rather than periphyton, but nutrient-biomass relationships are not well understood for macroalgae.

In assessing the consequences of nutrient enrichment in these waters you would need to take into account mixing conditions and tidal flushing, as they affect the mixing of river and coastal waters and whether N or P is limiting unwanted plant growth. Sedimentation may well be a more important issue in estuaries than unwanted plant growth stimulated by excessive nutrient concentrations.

Again, from an integrated catchment management perspective, nutrient controls for regulating river periphyton blooms should also be targeted at preventing macroalgae blooms. This reinforces the earlier comment that both N and P should be managed.

3.9 In considering (at least some of) the above questions, it might be useful to consider specific cases where possible. Two examples (the Manawatu and Rangitikei catchments) are reproduced here from the project brief:

3.9.1 ***The example of the Upper Manawatu catchment can illustrate this. P may currently be the limiting nutrient element, but this could be due to the very high N levels. Currently, P seems the most sensible target. However, due to elevated natural background levels, P concentrations may never be able to be reduced to the level where it will limit periphyton growth to the desired level*****.**

Answer:

See comments above. Management of blooms is about restricting both magnitude and duration. Even though background P levels might be moderately high, benefits to specific values can be achieved by reducing anthropogenic sources of P in streams and rivers. Both N and P need to be managed because of the interconnectivity of waterways (where different nutrients might be limiting in the same stream network), and because of temporal changes in N:P ratios and in periphyton response. Thus standards for managing both N and P are recommended.

3.9.2 ***A different example is the Rangitikei catchment, where N levels are not high, due to limited intensification of land use (e.g., dairying) compared to the Manawatu Catchment. Some NDS surveys have shown N to be the limiting nutrient in all surveyed parts of the Rangitikei catchment (Death & Death 2005). What nutrient should be targeted for management in the Rangitikei? Particularly as this catchment is facing increased land use intensification which, if permitted, would most likely result in at least some increase in stream N levels even if based on best management practice.***

Answer:

Given the hydrological regime and substrate characteristics of the Rangitikei, we would expect that enrichment of this river would easily promote periphyton blooms. Given the extent of Tertiary siltstone in the catchment, we would predict that N is the limiting nutrient. However, consistent with the notes above, both nutrients should be managed unless P is at extremely high levels (which we understand that it isn't).

3.10 General comment: Nutrient management strategies need to be considered together with other key contaminants – particularly pathogens and sediment.

Answer:

This was agreed to at the workshop with regard to managing specific land uses (section **3.4.2**), and protection of estuarine and coastal waters (section **3.8**). Many management practices aimed at reducing inputs to surface waters achieve reductions in more than one contaminant. For example, wetlands used for intercepting nitrate and promoting denitrification also trap P and faecal organisms (Nguyen et al. 2002a, b). Specific on-site management practices (nitrification inhibitors to reduce nitrate losses, optimal use of fertiliser P) do not have the same multipurpose functionality as do interception methods along runoff pathways. Nevertheless, it is important to decide on the priority pollutant(s) and choose management strategies that are most appropriate. For example, if P is the target then maintaining fertiliser application rates so that the optimum Olsen P levels are not exceeded will be highly effective in reducing P inputs to waterways (McDowell 2004).

3.11 Some issues that were not covered by the pre-circulated questions

3.11.1 Severity of nutrient limitation

Algal growth that is near-replete or near-balanced will not respond to enrichment with the limiting nutrient to the degree that severely-limited algae or severely-imbalanced growth will. A crude index of the severity of limitation is Gnut:Gcon (ratio of growth in limiting nutrient treatment to growth in controls: see Francoeur et al. 1999). Periphyton tissue ratios of PN/PC (or %N) and PP/PC (or %P) relative to Redfield ratios for balanced growth, also provide an index of severity of limitation (Healey 1985). Note that severity of nutrient limitation is not dependent on algal biomass; it is dependent on the relative availability of nutrients, and other limiting resources.

3.11.2 Interactions or hierarchies of limiting resources

Nutrient limitation is rarely severe when light is limiting, because nutrient acquisition is generally chemical-energy dependent. “Generally” nutrient uptake is decoupled from light-dependent energy production, because some nutrient acquisition processes are passive, and because acclimation in plant cells can lead to nutrient-for-light tradeoffs (e.g., through increased pigment synthesis).

3.11.3 Response to the rate of nutrient supply

Nutrient acquisition in algae and consequent growth are not a response to nutrient concentration *per se*, but a response to nutrient supplies to cell surfaces (in mass/surface area/time). That means that velocity and concentration are compensatory. All other factors being equal, algae in fast, nutrient-poor water can grow as fast as algae in slow, nutrient rich water.

3.11.4 N-fixation

Some cyanobacteria are capable of fixing dissolved atmospheric nitrogen (N_2 gas) into organic N thus making them independent of other sources of nitrogen, and this is often cited as a reason to expect P-limitation. That may be true for N-fixing taxa, but is not necessarily true for whole algal assemblages and studies on the influence of P on the contribution of cyanobacteria to periphyton communities have shown variable responses (Borchardt, 1996). N-fixing species are generally favoured by high levels of P and temperature, so that measures to control these factors should also prevent periphyton escaping N-limitation via cyanobacteria proliferation. Broadscale studies of periphyton communities in New Zealand (Biggs 1990) indicate that cyanobacteria are a lesser component in our rivers than elsewhere, and that filamentous green algal species, such as *Cladophora* and *Rhizoclonium* are associated with highest periphyton biomasses. In summary, we consider that restricting N loads to the level that limits green algae and diatoms will be effective in controlling nuisance periphyton biomass.

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6. Appendix 1

Method used by Horizons Regional Council for periphyton SOE monitoring

Five representative stones were collected from each site (where possible) and frozen for later analysis of periphyton biomass. Pigments were extracted using 90% acetone at 5°C for 24 hours in darkness. The amount of chlorophyll *a* in the acetone extract was measured using a spectrophotometer to read the absorbances at 750, 665 and 664 nm. Acid was added to convert the chlorophyll *a* to phaeophytins before re-reading. Mean chlorophyll biomass, as measured by chlorophyll *a* (mg/m^2) was calculated on a per site basis. Corrections were made for stone surface area using the three dimensions of the stone (Graham et al. 1988) and assuming only the top half of the stone was exposed to light and thus suitable for periphyton growth. At each site the percentage of substrate covered by algae in each of the SHMAK enrichment indicator categories was visually assessed (as detailed in Biggs & Kilroy 2000). The percent cover in three 1 m^2 replicate quadrats perpendicular to the river bank was assessed at three equidistant transects along the study reach. The assessment was made according to the following categories: 1 = <5%, 2 = 5-50% and 3 = >50%. This data was converted to percent cover in the relevant categories and compared to the Ministry for the Environment guidelines (Biggs 2000) presented in Table 1. Values less than or equal to the recommended limits were considered acceptable.

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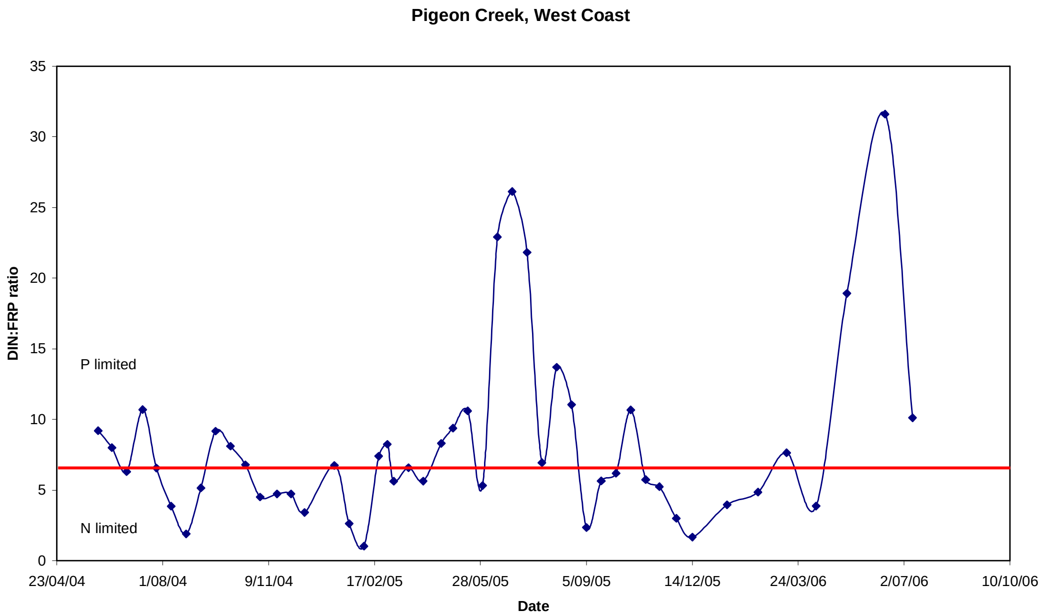
7. Appendix 2

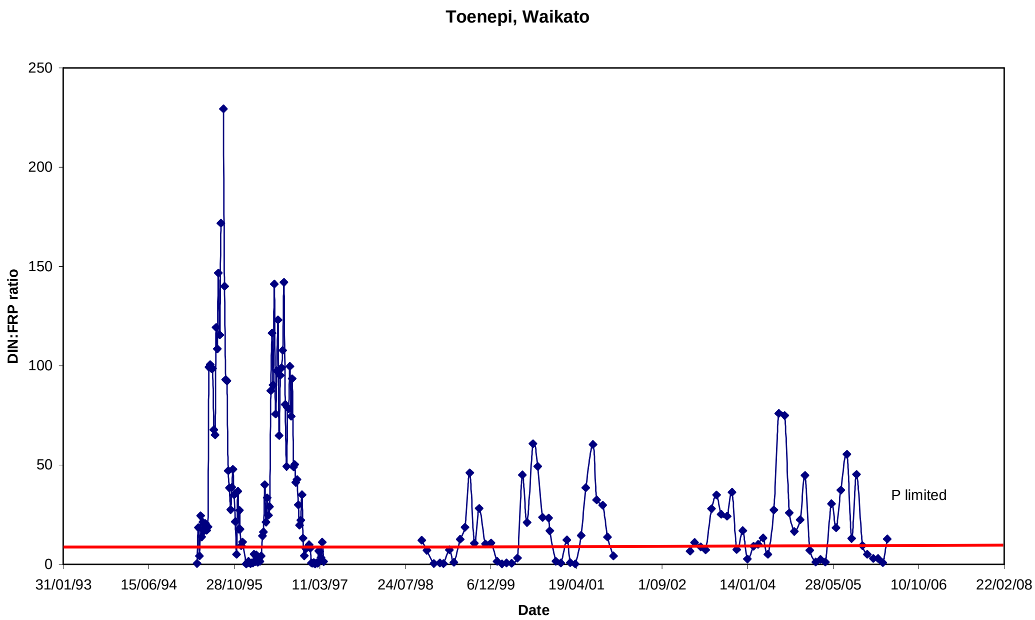
Seasonal variations in dissolved DIN:DRP ratios from monitored dairy catchment streams showing temporal and/or seasonal variations (R. Wilcock, NIWA, unpublished data). The graphs refer to FRP (filterable reactive P), which is another way of describing DRP. The first example (Pigeon Creek) is of a stream in a high rainfall area where nitrate N (NO_3-N) is a relatively small component of dissolved inorganic nitrogen and ammonia N (NH_4-N) is the major component. This is atypical for dairy catchment streams in New Zealand. The red line indicates the Redfield weight ratio (7:1 for DIN:DRP). The data show that in this instance both elements are "limiting" plant growth at different times of the year. Pigeon Creek is a stony, hard-bottom stream and has summer blooms of periphyton and filamentous green algae (Wilcock et al. 2006a).

(a) Pigeon Creek, Lake Brunner catchment (annual rainfall about 5 m)



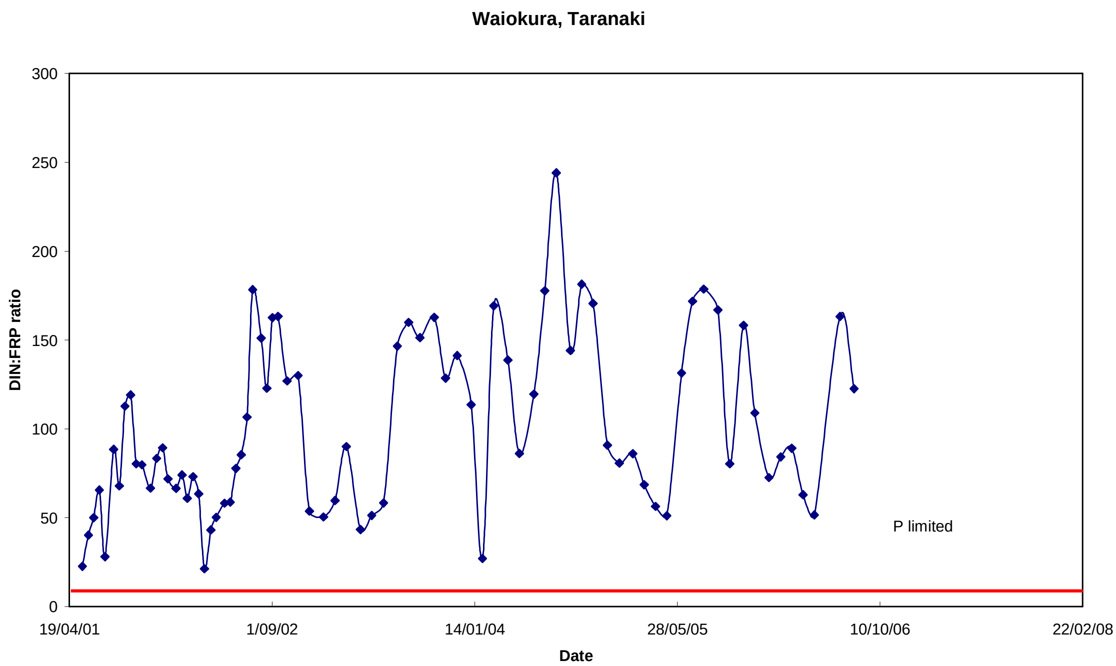
(b) Toenepi Stream, Morrinsville, Waikato

Toenepi Stream is located near Morrinsville in the Waikato region and is a tributary of the Piako River. The region has an annual rainfall of about 1200 mm with wet winters and a 4-6 week summer drought during January-March. During the summer low flow period the stream is “N limited”, whereas at other times it is P limited. The stream is soft-bottomed and at times has a high biomass of emergent macrophytes, notably *Persicaria* sp. (swamp willow weed), as well as submerged macrophytes (*Potamogeton* spp., *Nitella hookeri* and *Nasturtium officianale*) and filamentous green algae (Wilcock et al. 2006b).



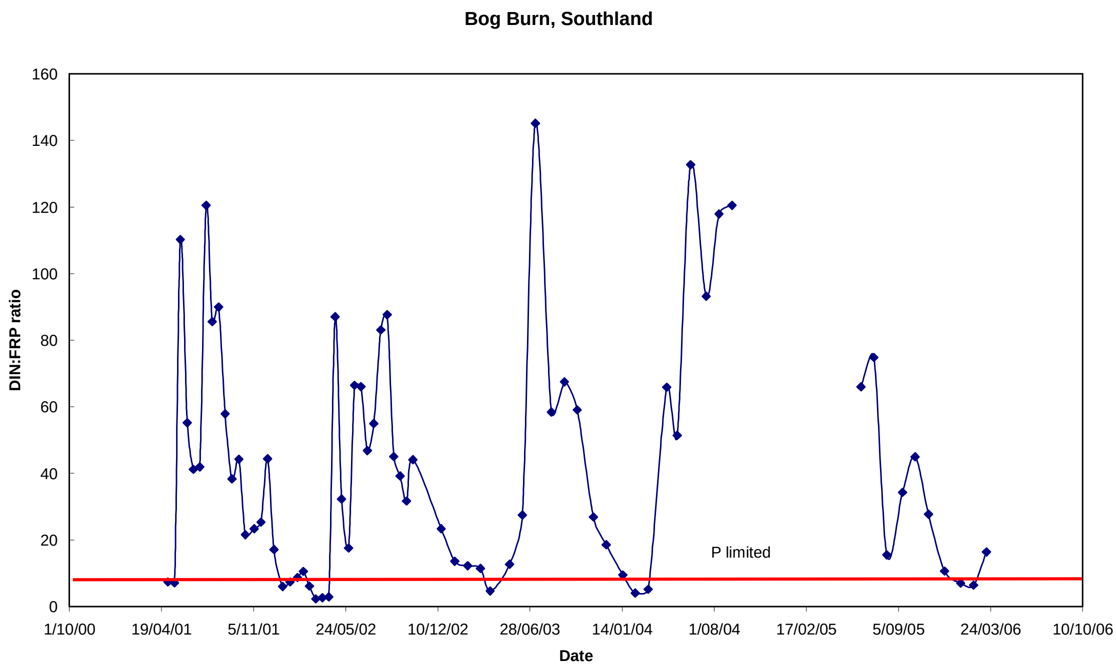
(c) Waiokura Stream, Manaia, Taranaki

Waiokura Stream is a soft bottom low-gradient stream on the Taranaki Ring Plain, near Manaia and receives over 30 discharges from dairy shed effluent ponds. The stream is characterised by moderately high NO_3-N concentrations (median about 3 g/m^3) with lower than average DRP concentrations (Wilcock et al. 2006a) and thus, is always above the Redfield line, or "P limited". The stream is reasonably well shaded and periphyton blooms are not regarded as a problem.



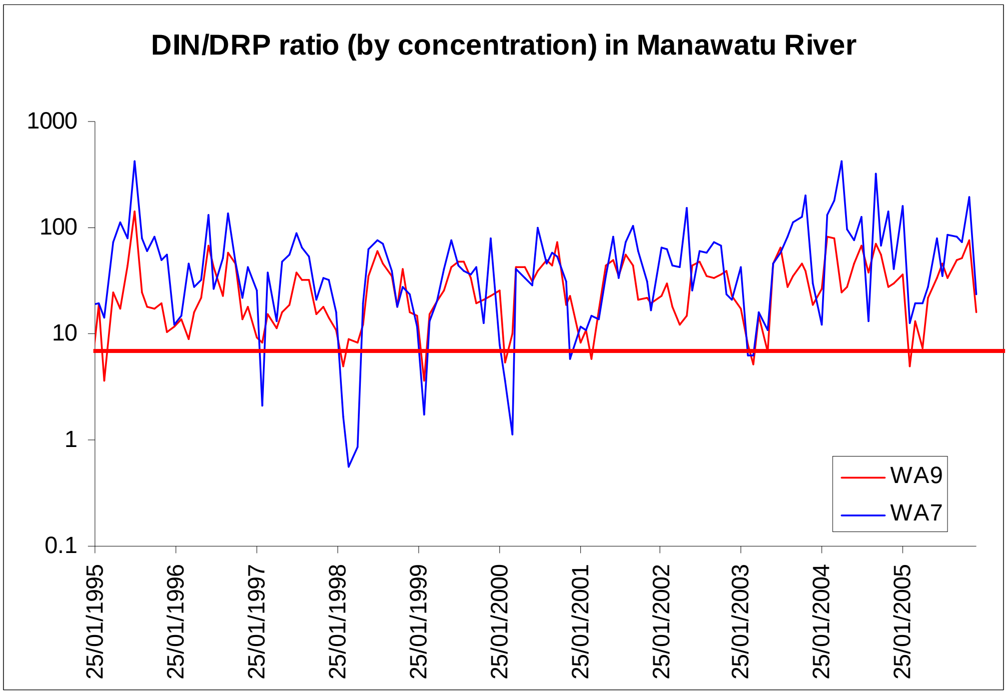
(d) Bog Burn, Central Southland

Bog Burn is a tributary of the Oreti River and is located in Central Southland, near Winton. Substrate is gravely but with abundant fine sediment. The stream receives numerous inputs from (mainly sub-surface) drains that also collect wastewater from irrigated dairy shed effluent (Monaghan et al. 2007). Like most dairy catchment streams, nitrate is the dominant N form and Bog Burn has a median NO_3-N concentration of 0.8 g/m^{-3} (lower than most dairy streams) and fairly typical DRP levels (median 0.02 g/m^{-3}) (Wilcock et al. 2006a). The stream is "P limited" for all times of the year except late summer, when the N:P ratio falls below the red line and the stream may then be N limited. Macrophyte cover is low but the stream does have periphyton mats and some filamentous green algae in summer.



(e) Manawatu River

Data from the National River Water Quality Network for two sites on the Manawatu River are shown. WA7 is an upstream site near Dannevirke and WA9 is a downstream site near the Opiki Bridge. The plot shows (i) the spatial differences in N:P ratios, and (ii) the seasonality and interannual variability of N:P ratios.



8. Appendix 3

Best Management Practices recommended have recently been derived for dairy in a variety of geoclimatic regions. Many of these are broadly applicable to a range of grazed pasture farming systems (e.g., beef cattle, sheep, mixed sheep/beef/deer) (Betteridge et al. 2005; Wilcock et al. 2006b; Monaghan et al. 2007)

Best Management Practices for dairy farms and other grazed pasture systems.

Target	Best Management Practice (BMP)
Faecal pollution	Fencing of all major waterways (i.e., stock exclusion)
	Minor earthworks that divert runoff from farm tracks entering streams, to sediment traps or to fields
	Deferred irrigation of dairy shed effluent to land (i.e., fewer pond discharges)
	Grass filtration strips in riparian zones
	Avoiding grazing saturated soils in order to minimise runoff losses
	Maximise soil infiltration by the use of stand-off pads in wet conditions – reduced overland flow
P	Deferred irrigation of dairy shed effluent
	Reducing soil P fertility to their economic optimum (NB this also reduces effluent losses of P)
	Open-drain vegetation (grasses) for trapping particulate P
	Avoiding soil compaction caused by overstocking
N	Nutrient budgeting to optimise farm nutrient inputs via fertiliser and imported feed
	Use of nitrification inhibitors
	Feedpad systems for wintering animals – avoiding the deposition of excreta N during times when drainage is likely
	Natural and constructed wetlands for enhancing denitrification losses