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Understanding variations in the limiting nitrogen and phosphorus status of rivers in the Manawatu-Wanganui Region, New Zealand

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Abstract

Nitrogen (N) and phosphorus (P) enrichment of waterways can affect their ecological, aesthetic and recreational values by causing excessive growth of nuisance algae and other organisms, collectively known as periphyton. In the past, P was commonly thought to be the 'limiting nutrient' for periphyton growth in many of the Manawatu-Wanganui region's rivers. Management of the Manawatu River in particular relied on reducing P inputs from point sources at low flows to avoid nuisance periphyton growth.

Long-term State of the Environment data on N and P were analysed against river flow for a number of sites in the region's river catchments. This paper presents the results from this analysis for the Manawatu and Rangitikei catchments.

Nutrient limitation status was found to vary at and between a number of sites in the Manawatu catchment and this variation was highly influenced by river flow. Specific low flow investigations of water quality in two catchments found large spatial variation in limiting nutrient status at a number of sites on the same day, within the same sub-catchment.

The One Plan (Manawatu-Wanganui combined Regional Plan and Policy Statement) proposes management of both N and P at all flows lower than substrate-disturbing floods (20th percentile flow). As more is learned about the interactions between nutrient concentration, flow and periphyton growth in enriched river catchments, it becomes clear that the best approach is a catchment-specific framework, based on the combined management of N and P, at relevant flow regimes.

Introduction

Like all plants, periphyton (the community of algal, fungal, bacterial and cyanobacterial organisms that grow within rivers and streams) needs space, light and nutrients in order to grow. Nitrogen (N) and phosphorus (P) in soluble and inorganic forms are available for uptake by periphyton in waterways; elevated concentrations of soluble N and P can lead to excessive or nuisance periphyton growth.

High concentrations of soluble N and P are found in many waterways throughout New Zealand (Scarsbrook, 2006; McDowell *et al.*, 2009) as a result of either direct (point source) discharges of waste (Quinn and Hickey, 1993), or from diffuse (non-point source) run off and leaching from catchment land (Quinn *et al.*, 1997a; Quinn and Stroud, 2002; Larned *et al*, 2004; Monaghan *et al.*, 2007; Ballantine and Davies-Colley, 2009a). The Manawatu River catchment in the Manawatu-Wanganui region is subject to considerable point (Quinn, 1985; Quinn and Gilliland, 1988; Biggs and Kelly, 2002) and non-point source nutrient enrichment (McArthur and Clark, 2007; Roygard and McArthur, 2008; Smith *et al.*, 2010). The Rangitikei River catchment is also affected by enrichment, but to a lesser extent (Roygard and Carlyon, 2004; McArthur and Clark, 2007).

High periphyton growth negatively affects the ecological and recreational values of waterways (Freeman, 1986; Biggs, 2000a; Biggs, 2000b). In recent years, the Manawatu and Rangitikei River catchments have been subject to extensive mats of potentially toxic cyanobacteria and large unsightly growths of green filamentous algae respectively. Since 2006, anecdotal observations of increasing periphyton in these catchments have highlighted a growing awareness of the effects of these growths on aesthetic and recreational values. However, the collection of empirical periphyton or bioassay data was limited to annual observations or one-off surveys, prior to the instigation of a region-wide monitoring programme in December 2008 (Kilroy *et al.*, 2008). Information regarding the limiting nutrient status of rivers was derived from water chemistry samples in the absence of reliable biological data.

The theory of nutrient limitation of plant and algal growth comes from the application of the Redfield molar ratio of 1:16 P to N (or 1:7 by weight) for optimal aquatic algal growth (Redfield *et al.*, 1963). The assumption is that if more than 16 moles of N are present for every mole of P, then growth is likely to be limited by the amount of P present (P-limited). Conversely, if there are less than 16 moles of N for every mole of P then growth is likely to be limited by the amount of N present (N-limited). This theory was applied to the management of the Manawatu River catchment in the late 1990s, where the regulatory and management focus (through the Manawatu Catchment Water Quality Regional Plan) was on reducing P from point sources to below the concentration thresholds required for periphyton proliferation, thereby inducing a P-limited system.

The nutrient limitation of a river system is often expressed as the ratio of P to N, as discussed above. Examination of nutrient ratios to determine limiting status was used by McDowell and Larned (2008) and McDowell *et al.* (2009) in their studies of national patterns in nutrient limitation. However, the raw concentration of nutrients is also of particular interest, as this is the actual state of nutrient condition experienced and influenced by aquatic communities such as periphyton. In this study the raw concentration of nutrients has been used for all analyses to determine potential nutrient limitation status. In any analysis of nutrient limitation, whether examining ratios or raw concentrations, researchers should be mindful of the influence of periphyton growth on in-river nutrient levels at the time of sampling, as periphyton biomass can have considerable effects on residual nutrient concentrations (Biggs, 1995; Biggs, 2000b; Soziak, 2002).

A nutrient-diffusing substrate study was undertaken in the Rangitikei River catchment (Death *et al.*, 2007) to determine whether assumptions about the Rangitikei River being ‘N-limited’ held true. Nutrient-diffusing substrates are *in situ* experimental plots, containing different levels of N and P, which diffuse through a medium placed on the river bed. The substrates are then left to grow periphyton over a controlled time period. This method is considered to be the most conclusive way of determining the limiting nutrient status of rivers and lakes (Fairchild and Lowe, 1984; Francoeur *et al.,* 1999; Biggs, 2000b; Death *et al.*, 2007).

However, the results are only a snapshot of the limiting nutrient condition at the time of each survey and may be constrained by the stable flows at which the experiment is possible, and by the species of periphyton that are able to colonise the artificial substrates. Some of the sites surveyed by Death *et al.* (2007) using this method showed results indicative of N limitation at the time of the experiment. Roygard and Carlyon (2004) also found results indicative of N limitation in their basic water quality assessment of the Rangitikei catchment.

The Proposed One Plan (Manawatu-Wanganui Regional Council's combined Regional Plan and Policy Statement) will eventually supersede the Manawatu Catchment Water Quality Regional Plan. Technical and expert advice received during the development of nutrient standards for the One Plan highlighted the need to manage both N and P (Wilcock *et al.*, 2007). Limiting only one nutrient was not deemed a reliable tool to reduce periphyton growth over the wide range of environmental conditions in the rivers of the region, given that nutrient limitation has been found to vary over time and in different reaches of some New Zealand streams (Quinn *et al.*, 1997b; Francoeur *et al.,* 1999; Biggs, 2000b; Biggs and Kilroy, 2004; Wilcock *et al., 2007*).

Consequently, through the objectives and policies of the One Plan, water quality standards have been proposed for both N and P in all waterways of the region at all flows less than the 20th exceedence percentile, to maintain the ecosystem, recreational and cultural values of the rivers.

The objectives of this study were to: 1) test whether assumptions of P limitation were broadly applicable to the region's rivers; 2) determine the factors influencing variability in limiting nutrient status among sites in two major river catchments; and 3) provide regionally relevant information on limiting nutrient status to support and validate the management of both N and P.

Methods

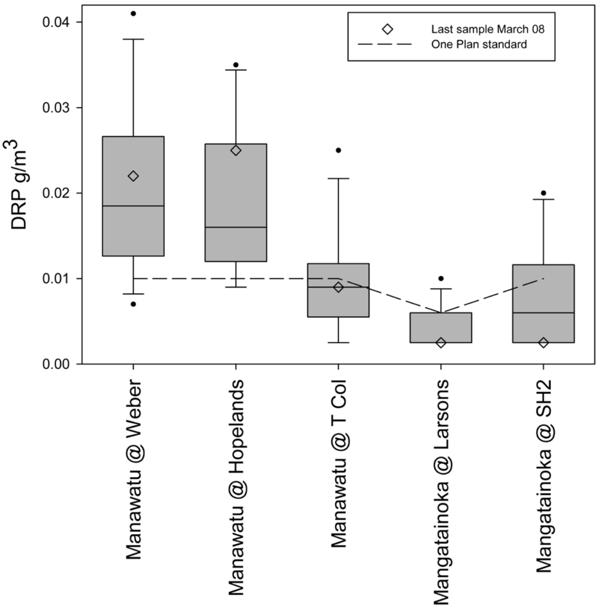
Water quality data for the box and whisker plots (Fig. 1) was collated from monthly State of the Environment (SOE) water quality monitoring between March 2007 and March 2008 at five sites in the Manawatu River catchment. Data for the scatter plots was also collated from monthly monitoring between 1989 and 2008 at three key sites in the upper Manawatu River catchment and one site in the middle Rangitikei River catchment (Fig. 2). All data expressed as N or SIN refers to soluble inorganic nitrogen and all data expressed as P or DRP refers to dissolved reactive phosphorus.

Concentrations of ammoniacal nitrogen and total oxidised nitrogen (nitrite and nitrate nitrogen) were summed to determine the SIN concentration for each sample. Raw DRP was plotted against the summed SIN concentrations. Any values below the level of analytical detection had the 'less than' sign removed and the datum halved, as per the recommendations of Scarsbrook and McBride (2007).

Flow at the time of sampling was determined from continuous hydrometric recorder stations. At all sites, except the Mangatainoka at State Highway 2, water quality samples were collected from the same location as the flow recorder. For the Mangatainoka at State Highway 2 site, flow from the Mangatainoka at Pahiatua Town Bridge site approximately 5 km upstream was used. Statistics for flow exceedence percentiles at each site were determined from Henderson and Diettrich (2007).

Results and discussion

The upper Manawatu catchment drains the south-eastern Ruahine and western Puketoi a)



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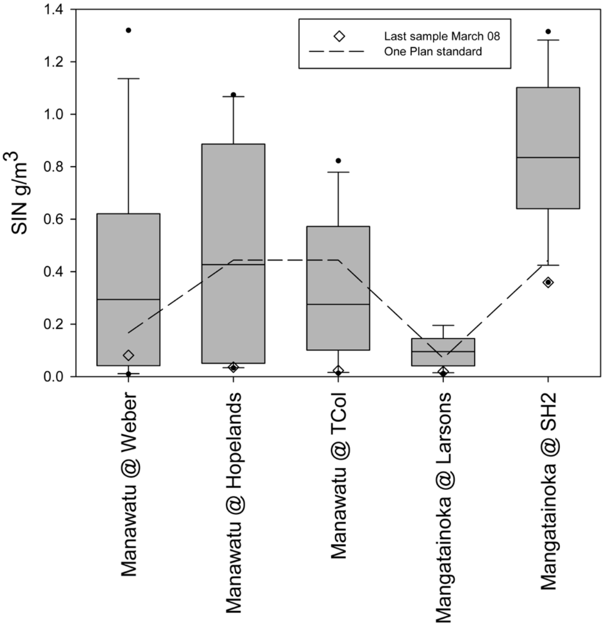


Figure 1 – Box and whisker plots of a) dissolved reactive phosphorus (DRP) and b) soluble inorganic nitrogen (SIN) concentrations at five monitoring sites in the upper Manawatu and Mangatainoka River catchments between March 2007 and March 2008 (n = 12). Central bar denotes median, box denotes inter-quartile range, whiskers are 10th and 90th percentiles and dots are outliers.

Ranges, encompassing ~127,000 hectares of largely pastoral land upstream of the Hopelands monitoring site. Sheep and beef farming is the predominant land use (69%), with dairying (16%) and native forest (10%) the other most common land-use types (Clark and Roygard, 2008). Diffuse inputs of N and P from land use in the catchment make up 98% and 80% of the N and P loads respectively (Roygard and McArthur, 2008) and the Dannevirke municipal sewage discharge contributes the majority of the remaining point-sourced nutrient load (McArthur and Clark, 2007). There are 147 dairy effluent discharges to land in the catchment and one dairy effluent discharge to water.

The Manawatu at Teachers College site is adjacent to Palmerston North and is considered as part of the lower Manawatu catchment. At this site the river receives inflows from a number of major tributaries, including the Tiraumea, Mangatainoka, Mangahao and Pohangina Rivers.

The Mangatainoka River is a major tributary of the Manawatu which originates from land draining ~49,000 hectares in the north-eastern Tararua Ranges. As in the upper Manawatu, sheep and beef farming is common (51%), with dairying (28%) and native forest (18%) making up the majority of the remaining land use (Clark and Roygard, 2008). Diffuse N and P make up 99% and 84% of the nutrient loads in the river respectively (Roygard and McArthur, 2008) and the Pahiatua municipal sewage discharge contributes the majority of the remaining nutrients, with minor contributions from Eketahuna sewage, Fonterra Pahiatua condensate and DB Breweries discharges (McArthur and Clark, 2007). The median DRP concentration upstream of the Pahiatua discharge is generally low (0.005 g/m^3), whereas the median downstream concentration is significantly higher (0.029 g/m^3) (Clark, 2010). The discharges make no significant contribution to N concentrations (McArthur and Clark, 2007). There are 97 dairy effluent discharges in the Mangatainoka catchment, all except one discharge to land.

The 2007/2008 summer was unusually dry for most of the central North Island. The upper Manawatu catchment and the Mangatainoka River were at record low flows from January to April, and flow restrictions were in place for most of the region's irrigation takes. In the Manawatu catchment upstream of the Hopelands monitoring site, where P has historically been considered the 'limiting nutrient', P concentrations sampled in mid-March during extreme low flows were higher than the median concentration for the 12 previous monthly samples (Fig. 1a). These results were relatively unexpected, given that nutrient concentrations are usually highest during elevated flows (Smith et al., 1996; Wilcock et al., 1999; Quinn and Stroud, 2002) and there are fewer mechanisms for P to reach waterways during dry conditions (McDowell et al., 2004). However, P concentrations overall were considerably higher at the upper two Manawatu sites when compared to the Mangatainoka and Teachers College sites (Fig. 1a). Soft sedimentary geology and greater P loads from diffuse and point sources all contribute to elevated P in the upper Manawatu (Eden and Parfitt, 1992; Parfitt et al., 2007).

Soluble nitrogen results for the same samples were extremely low (below the level of detection) at all three Manawatu mainstem sites (Fig. 1b). These findings suggest that two key processes may have been at work during this low flow event in the upper Manawatu:

1) P was influenced by point source inputs and potentially being released from bed sediments and becoming bioavailabile during low flow conditions (B. Wilcock pers. comm.; Parfitt et al., 2007), and
2) periphyton growth was potentially N-limited, unlike previous assumptions of general P limitation.

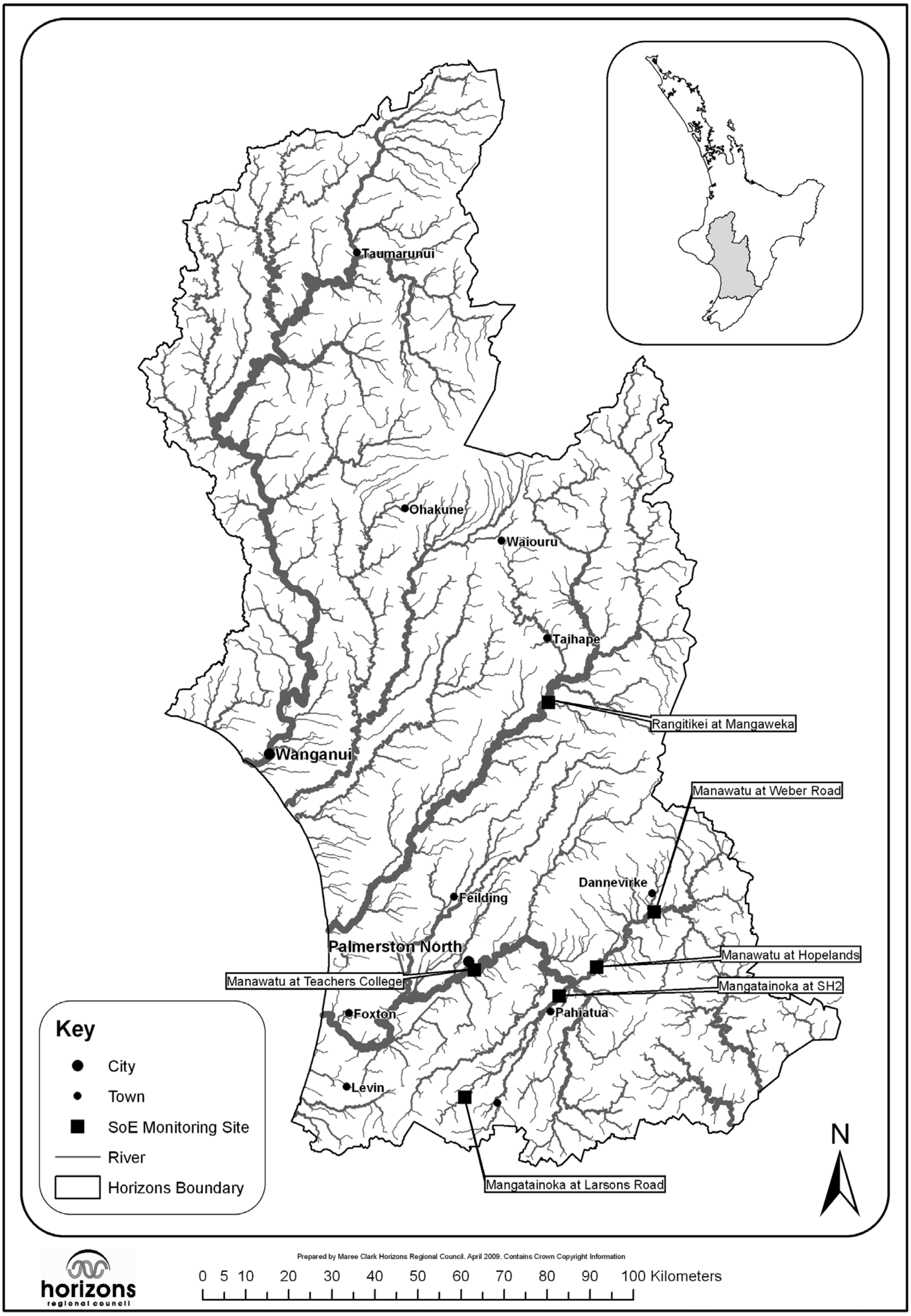


Figure 2 – Map of sites in the Manawatu-Wanganui region used for the nutrient limitation investigation.

The implications of this finding are significant for resource management and regulation. Nitrogen is derived almost entirely from diffuse inputs in the upper Manawatu and Mangatainoka catchments (Roygard and McArthur, 2008). Controlling N therefore requires control of land uses, such as intensive agriculture, which contribute proportionally greater amounts of soluble N per hectare (Wilcock et al., 1999; Monaghan et al., 2007; Clothier et al., 2007; McDowell et al., 2009). The One Plan proposes rules controlling N input from dairy farming, intensive sheep and beef, cropping and horticulture, in combination with greater controls on point source inputs to meet nutrient concentration standards in the river (for both N and P).

In the Mangatainoka catchment, the results contrasted noticeably with those from the three Manawatu mainstem sites. Nitrogen in the Mangatainoka River commonly reaches high concentrations (McArthur and Clark, 2007; Roygard and McArthur, 2008; Ballantine and Davies-Colley, 2009b). During March 2008, concentrations of both DRP (Fig. 1a) and SIN (Fig. 1b) at the Mangatainoka at Larsons site (upper Mangatainoka catchment) were below the level of detection. Over the same period, although the N concentration at the downstream Mangatainoka at State Highway 2 site (lower catchment) was not 'extremely low' when compared to the Manawatu mainstem sites, it was still below the 10th percentile of the results for the preceding twelve months.

These results suggest that high concentrations of P entering the water from the Pahiatua sewage discharge upstream of the State Highway 2 site were being taken up by periphyton, reducing downstream residual concentrations (Biggs, 1995; Biggs, 2000b; Soziak, 2002). The results also suggest that at the same time that the upper Manawatu River was N-limited, the Mangatainoka River was P-limited in the middle to lower reaches (near the State Highway 2 site).

Further investigation of the long-term record of SIN and DRP concentrations in the upper Manawatu and Mangatainoka catchments was undertaken following analysis of the results from March 2008. The potential for nutrient limitation was examined by applying the nutrient standards for controlling periphyton growth recommended by Ausseil and Clark (2007) and proposed in the One Plan (Table 1) to all SIN and DRP data collected since 1989 at the Manawatu at Weber Road and Manawatu at Hopelands monitoring sites, and since 1993 at the Mangatainoka at State Highway 2 site.

The Weber Road and Hopelands sites are central SOE monitoring sites in the upper Manawatu catchment, due to their catchment position downstream of areas with high proportions of pastoral land use and the length and quality of the hydrometric

Table 1 – One Plan proposed standards for soluble nitrogen and phosphorus concentrations (conc.) in relation to potential nutrient limitation status for three river catchments in the Manawatu-Wanganui region. *Note: to satisfy the limitation status, both soluble inorganic nitrogen (SIN) and dissolved reactive phosphorus (DRP) conditions must be met for any observation.*

Limitation status	SIN conc. (Manawatu & Mangatainoka)	SIN conc. (Rangitikei)	DRP conc.
Co-limited	< 0.444 g/m^3	< 0.110 g/m^3	< 0.01 g/m^3
N-limited	< 0.444 g/m^3	< 0.110 g/m^3	> 0.01 g/m^3
P-limited	> 0.444 g/m^3	> 0.110 g/m^3	< 0.01 g/m^3
Unlimited	> 0.444 g/m^3	> 0.110 g/m^3	> 0.01 g/m^3

and water quality records collected at these sites. When the data for all flows was examined for the Manawatu at Weber Rd (Fig. 3) and Manawatu at Hopelands sites (Fig. 4) it became clear that there was no 'average' limiting nutrient status at either site. Observations were collected that were either P- or N-limited. This relationship may have been influenced by flow at the time of sampling, so to better understand the influence of flow on P and N limitation, the results for the Manawatu at Hopelands site were plotted according to four flow categories (Fig. 5). The Manawatu at Hopelands site was selected for more detailed analysis, as it is the key monitoring site in the upper Manawatu, as it includes the contributing land area (between Weber Road and Hopelands) with the most intensive land use (dairying) in the catchment.

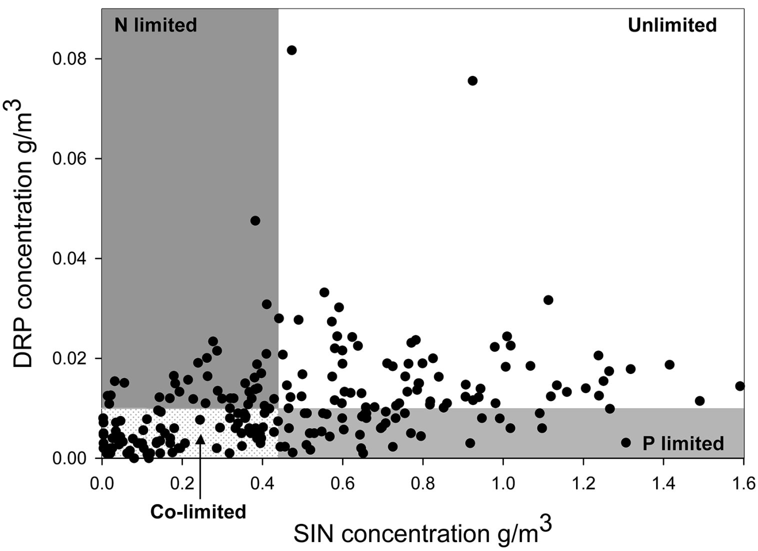


Figure 3 – Soluble inorganic nitrogen (SIN) and dissolved reactive phosphorus (DRP) concentration from samples collected monthly from the Manawatu at Weber Road SOE monitoring site between 1989 and 2006, displayed with potential nutrient limitation status determined using One Plan proposed nutrient standards. *NRWQN data courtesy of NIWA.*

Figure 5 shows the influence of flow on nutrient limitation status in the Manawatu at Hopelands. At low flow (Fig. 5a), there was no clear pattern exhibited by either nutrient. However, at flows lower than median (Fig. 5b) there were fewer co-limited (meaning there was unlikely to be enough input of both N and P to stimulate periphyton growth), and more unlimited observations. Phosphorus and N limitation was still found in roughly equal numbers of observations.

For higher flows (above median, Fig. 5c) little nutrient limitation of any kind was observed, and for flows in the top 10th percentile (exceeded 90% of the time, Fig. 5d) all observations except two were unlimited by either N or P. Elevated nutrient and sediment concentrations at high river flows are not uncommon in some catchments in New Zealand (Smith *et al.,* 1996; Wilcock *et al.,* 1999; Quinn and Stroud, 2002). The potential for adverse effects from nuisance

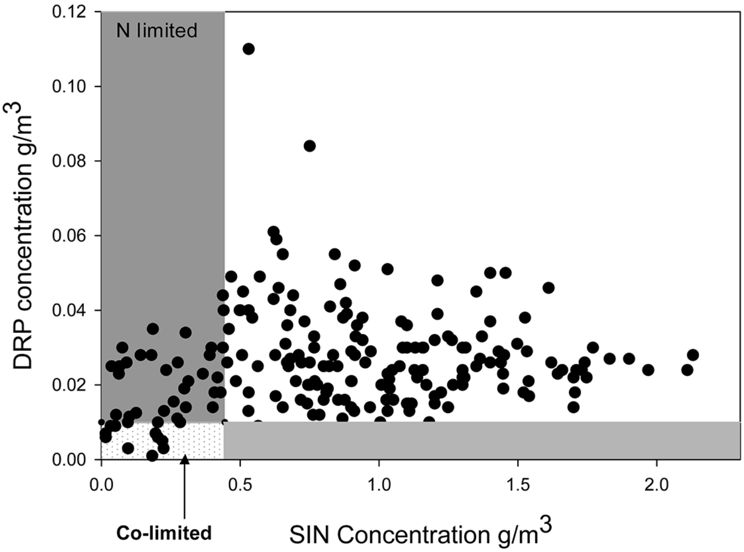


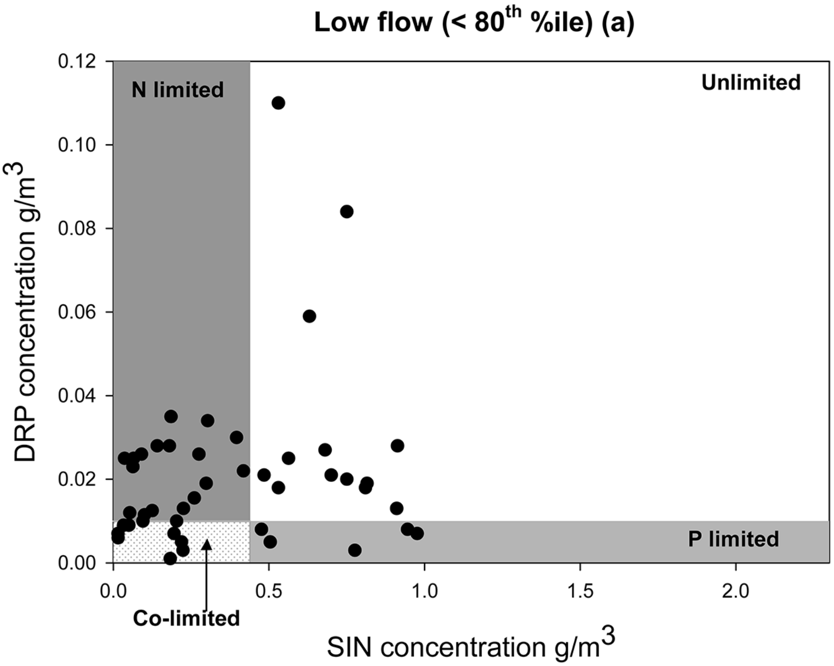
Figure 4 – Soluble inorganic nitrogen (SIN) and dissolved reactive phosphorus (DRP) concentration from samples collected monthly from the Manawatu at Hopelands SOE monitoring site between 1989 and 2008, displayed with potential nutrient limitation status determined using One Plan proposed nutrient standards.

periphyton growth is commonly vastly reduced during such flows because at these times periphyton is limited by turbidity, temperature and substrate movement or abrasion (Biggs, 1995; Biggs, 2000b; Biggs and Kilroy, 2004). The Proposed One Plan standards for SIN and DRP account for this phenomenon by applying only at flows of less than three times the median. However, contaminant loads exported to downstream and coastal environments should be considered when applying flow-related water quality standards.

Data collected monthly during a low flow investigation of water quality and aquatic ecosystem health at 20 sites in the upper Manawatu catchment in January and February 2007 (Clark *et al.*, 2009) was analysed for potential limiting nutrient status (Fig. 6). Although these results are based on only two data points at each sub-catchment site, the map indicates that nutrient limitation status can change quickly over spatial scales (e.g., different sub-catchments had differing nutrient limiting status during the same survey) and over time. Changes in limitation status over time can be associated with nutrient uptake from periphyton growth (Biggs, 1995; Biggs, 2000b; Soziak, 2002), changes to direct nutrient inputs such as discharges, or changes in flow. The flow percentiles for the January and February observations at the Hopelands site were the 89th and 96th exceedence percentiles respectively, so in this instance nutrient limitation status changed during receding flows. Conversely, increased flow from rainfall within sub-catchments also can change the nutrient limitation status rapidly at a site.

When SIN and DRP data for all flows was examined for the Mangatainoka at State Highway 2 site, the situation was quite different from the upper Manawatu results (Fig. 7). The Mangatainoka samples showed a clear pattern of P limitation or unlimited nutrient status for most samples.

a)



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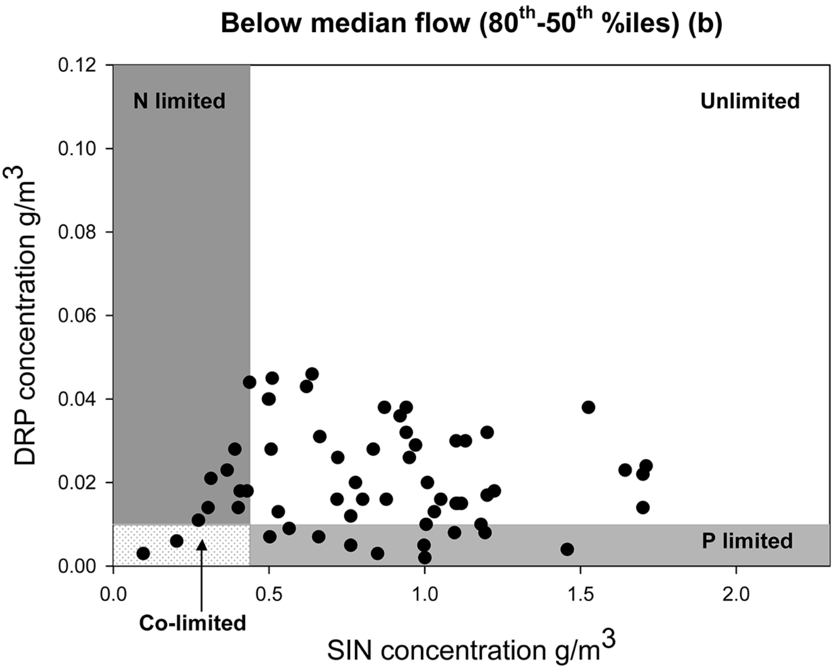
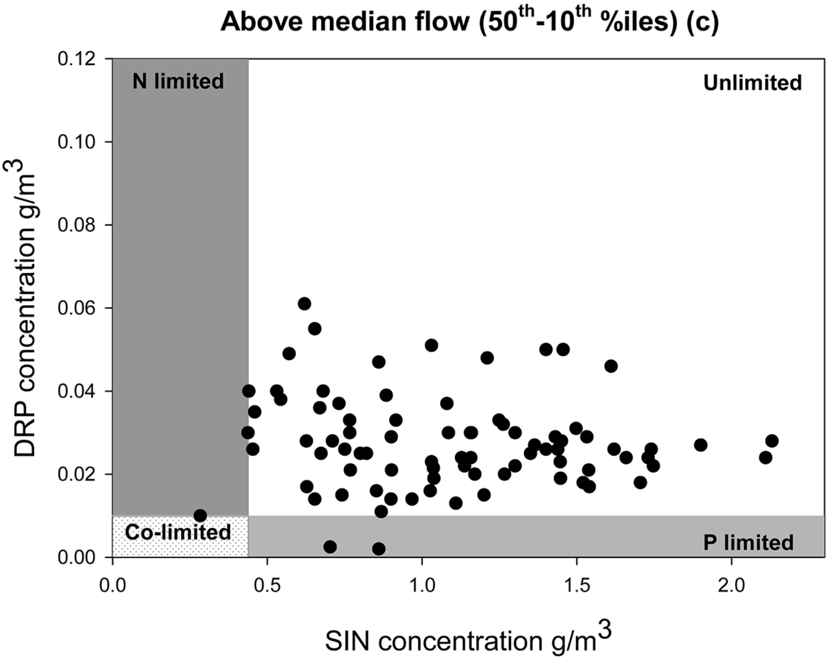
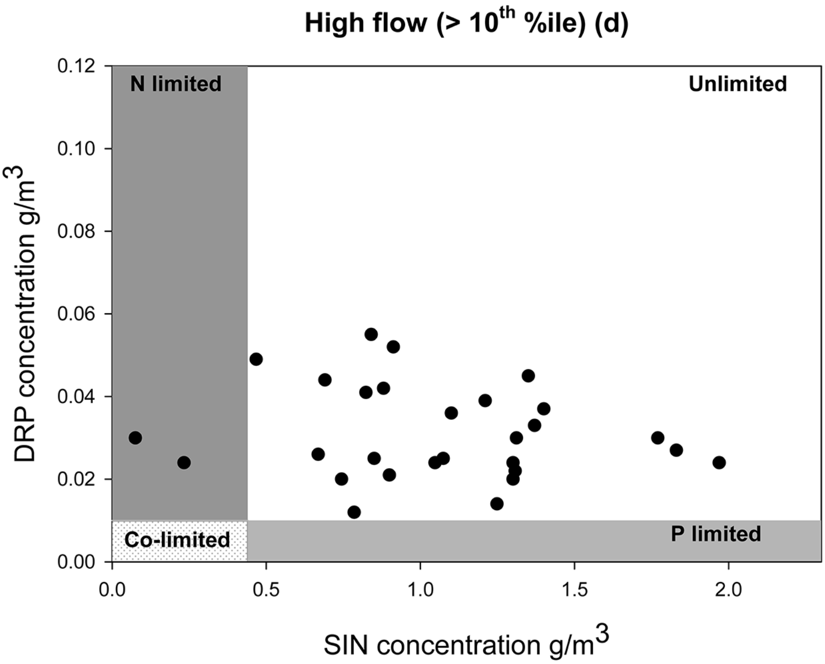


Figure 5 – Soluble inorganic nitrogen (SIN) and dissolved reactive phosphorus (DRP) concentration from samples collected at Manawatu at Hopelands monitoring site between 1989 and 2008 under varying flows:
a) low flow (< 80th percentile), b) below median flow (50th–80th percentile),

c)



d)



c) above median flow (50th–10th percentile), and d) high flow (> 10th percentile), displayed with potential nutrient limitation status determined using One Plan proposed nutrient standards.

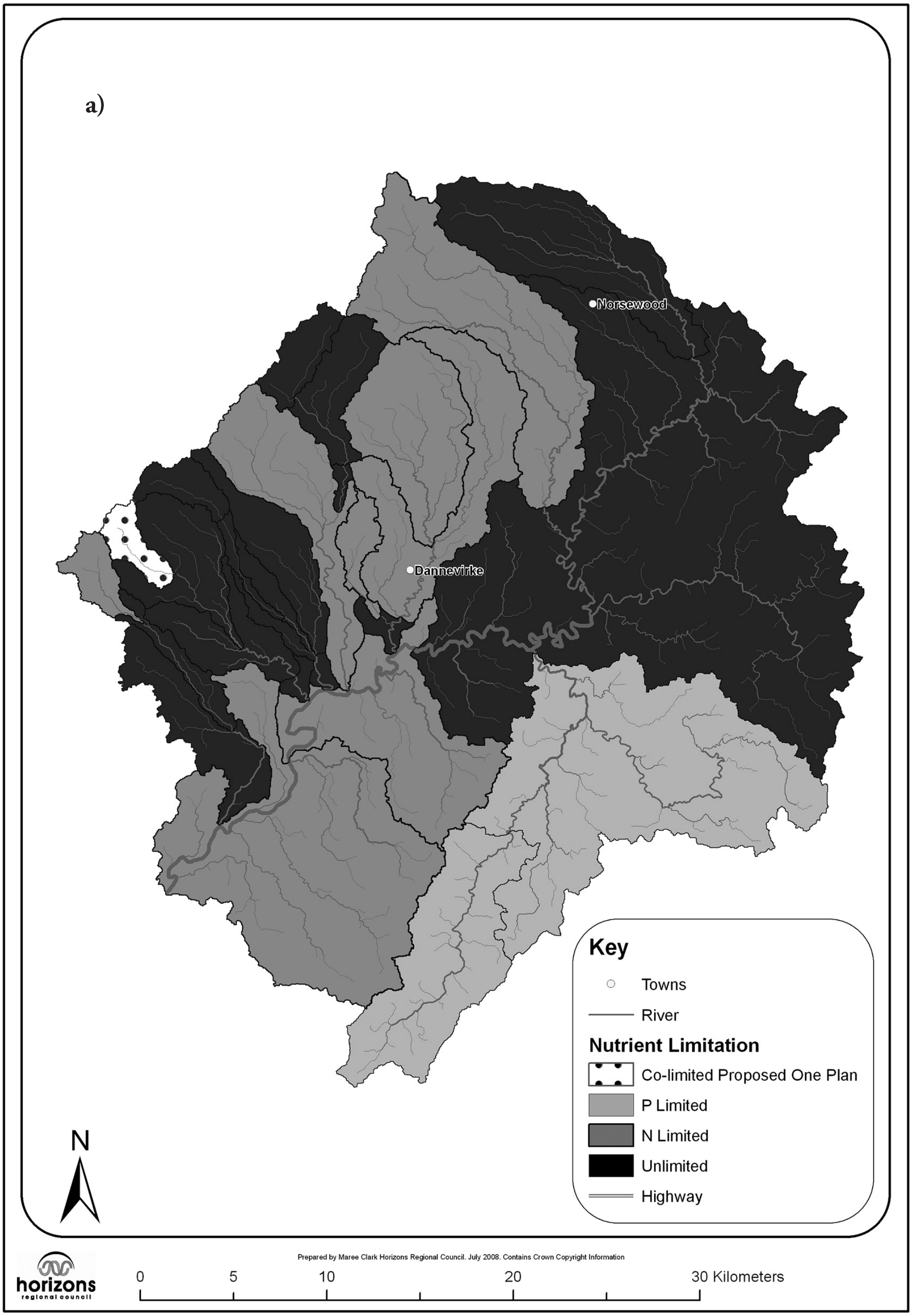
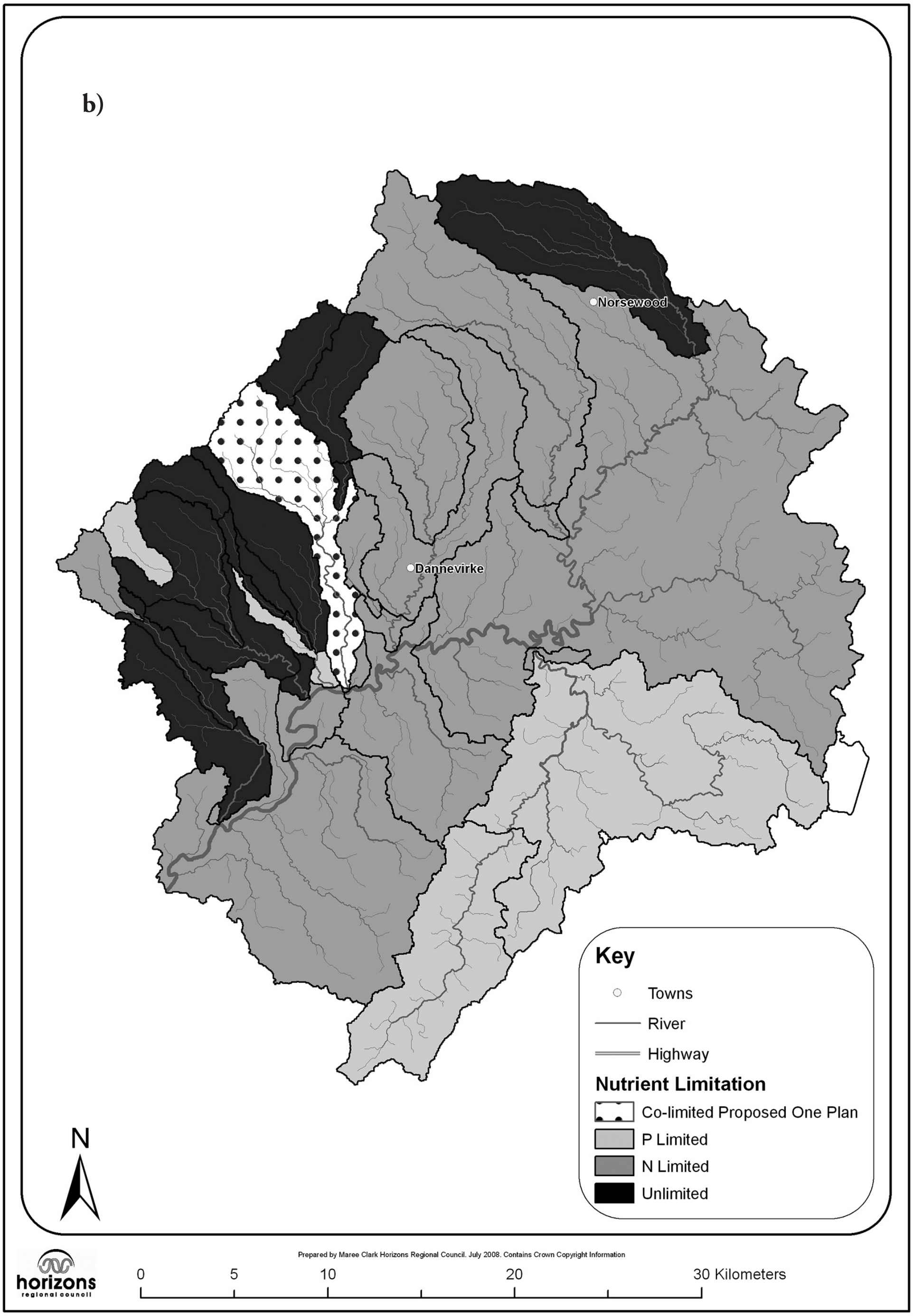


Figure 6 – Maps of sub-catchment nutrient limitation status in the upper Manawatu catchment on two monitoring occasions in early 2007.
Map a) represents sampling in January 2007 at the 89th percentile of flow in the Manawatu River at Hopelands.



Map b) represents sampling in February 2007 at the 96th percentile of flow measured in the Manawatu River at Hopelands.

However, a one-day investigation of water quality at 43 sites during low flows in the Mangatainoka catchment in February 2008 (Clark *et al.*, 2008) suggests that, as in the upper Manawatu catchment (Fig. 6), limiting nutrient status varies between sampling sites across the Mangatainoka catchment (Fig. 8).

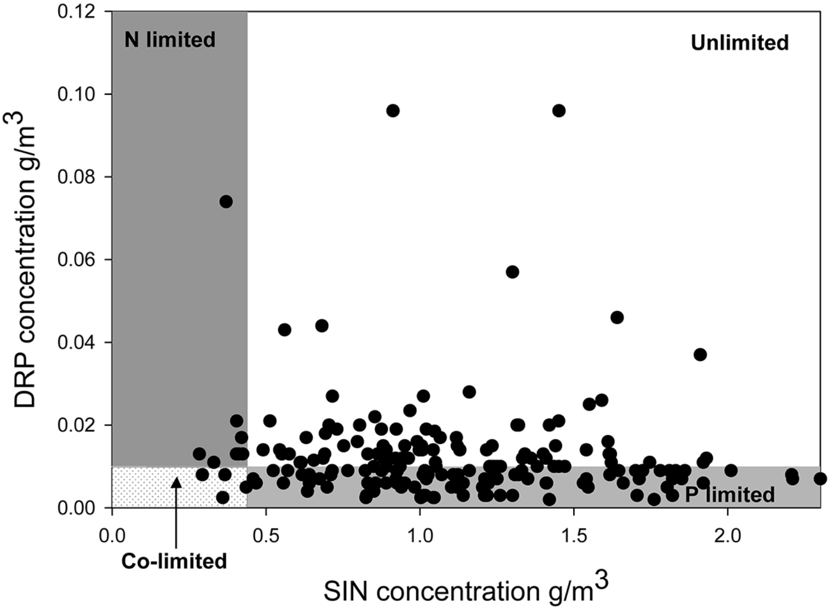


Figure 7 – Soluble inorganic nitrogen (SIN) and dissolved reactive phosphorus (DRP) concentration from samples collected at Mangatainoka at State Highway 2 monitoring site between 1993 and 2008, displayed with potential nutrient limitation status determined using One Plan proposed nutrient standards.

The Rangitikei catchment drains the Kaimanawa and north-western Ruahine Ranges, covering an area of ~217,550 hectares upstream of the Mangaweka monitoring site. Land use is predominantly sheep and beef farming (45%) and native cover (39%). Nutrient concentrations in the Rangitikei River are generally lower than in the Manawatu catchment, with a large number of co-limited observations (Fig. 9), reflecting the higher proportions of native cover and less intensive agriculture in the upper and middle catchment. More stringent N standards have been proposed in the One Plan for the Rangitikei River than for many sites in the Manawatu catchment (Table 1), to ensure that the current adverse effects of nutrient inputs do not become significant over time as a result of land-use intensification.

By contrast with the Manawatu catchment, the Rangitikei River has been considered to be predominantly N-limited in the past (Roygard and Carlyon, 2004; Death et al., 2007). Data collected from monthly SOE monitoring of the Rangitikei at Mangaweka between 1989 and 2008 suggests that variation in potential limiting nutrient status occurs here too (Fig. 9).

The findings of this study have significant implications for managing the adverse effects of nutrient enrichment in rivers. The relationships between nutrient limitation, periphyton growth, river flow and nutrient sources are extremely complex.

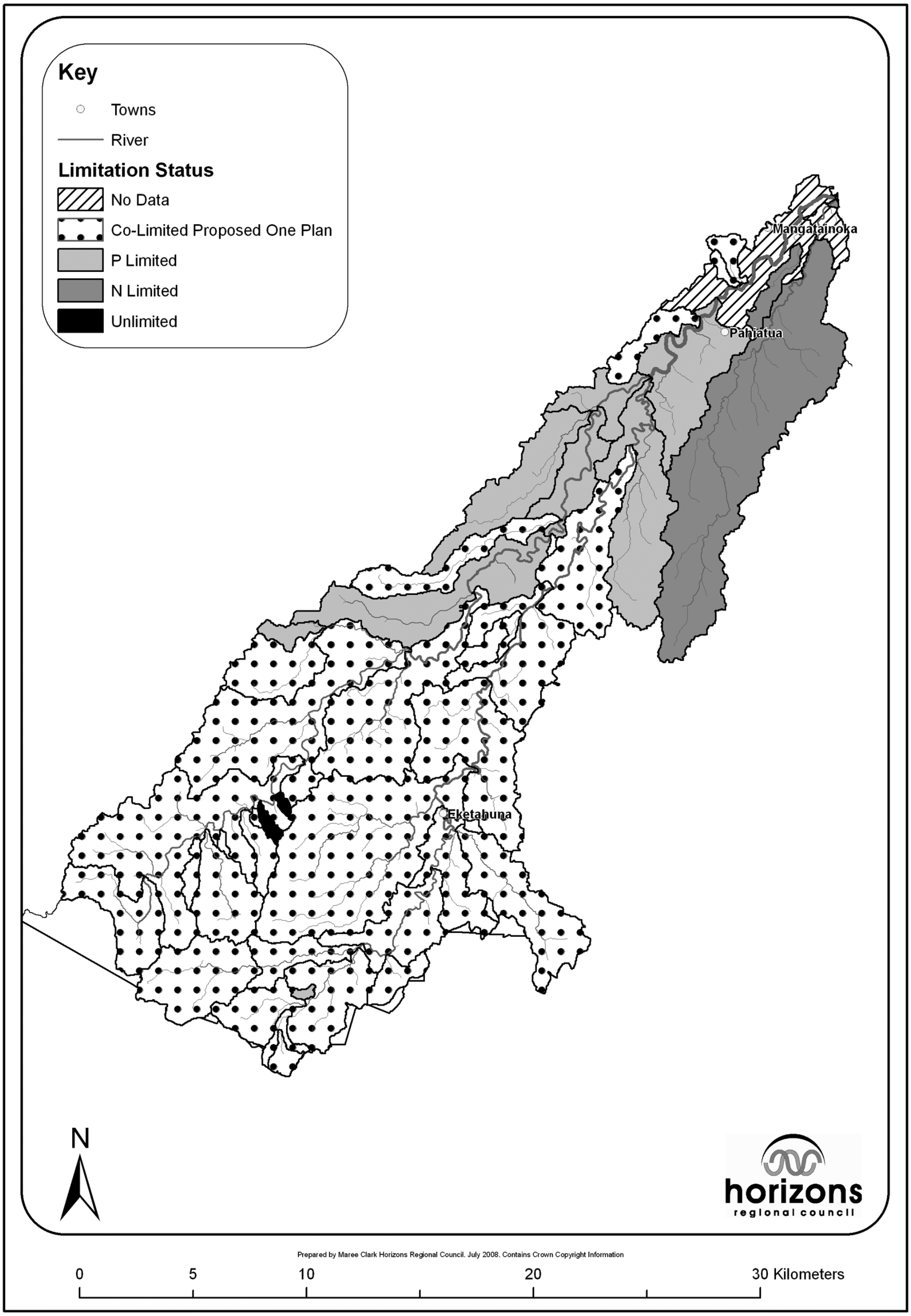


Figure 8 – Potential limiting nutrient status in the Mangatainoka River catchment during low flows (< 99th flow percentile for the Pahiatua at Town Bridge flow site) February 2008, based on One Plan standards.

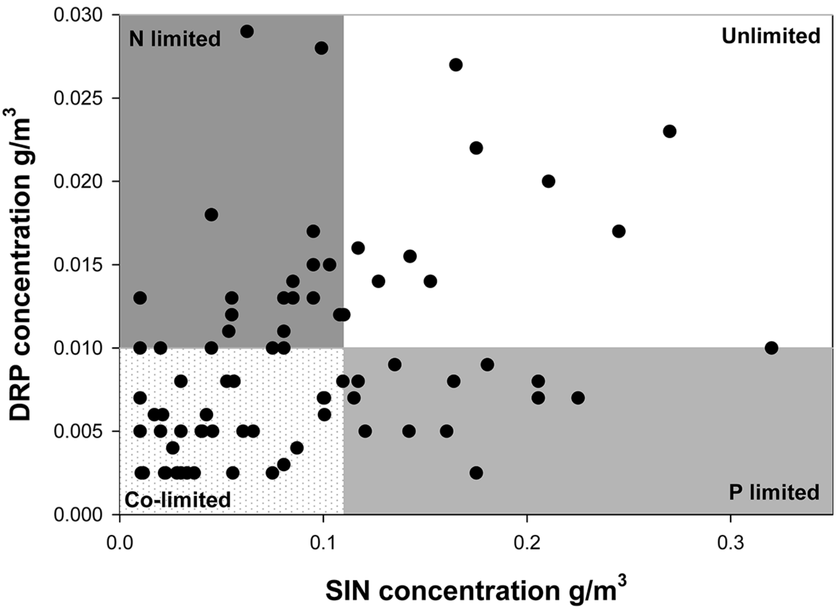


Figure 9 – Soluble inorganic nitrogen (SIN) and dissolved reactive phosphorus (DRP) concentration from samples collected from the Rangitikei at Mangaweka monitoring site between 1989 and 2008, displayed with potential nutrient limitation status determined using One Plan proposed nutrient standards. *Note: the Rangitikei N standard differs from the upper Manawatu and Mangatainoka standard presented above.*

The mechanisms by which nutrient enters rivers, and thereby the mechanisms for control of enrichment, differ between sources and between N and P (Davies-Colley and Wilcock, 2004; Roygard and McArthur, 2008; McDowell et al., 2009). Direct inputs from point sources can be, in many circumstances, fine-tuned to match in-stream concentration and flow conditions on a daily time scale, whereas diffuse inputs of N and P are strongly influenced by flow and land use, and the mechanisms for control, such as nutrient reduction through best practice or mitigation, are fairly coarse and occur on annual or greater time scales (Clothier et al., 2007; Parfitt et al., 2007).

Managing activities to reduce the nutrient enrichment of rivers requires a combined approach that addresses the complexities of variation in limiting nutrient status, flow, time and nutrient source in a manner which maximises the environmental outcomes but is simple enough for the development of clear and certain resource management policies and rules. The One Plan proposes such an approach through the use of water quality standards and regulatory controls on nutrient losses from intensive farming systems in catchments with compromised water quality.

Conclusions

Key messages from the results of the nutrient limitation investigation were:

1. nutrient limitation varies with time, flow and by sub-catchment location;
2. managing such a dynamic system via control of one 'limiting nutrient' is likely to fail as a result of the complexities in these relationships; and

3. management of the adverse effects of enrichment requires an approach which limits the inputs of both N and P to waterways, across all nutrient sources and under most flow conditions.

Further work is underway in other major river catchments to examine the factors affecting nutrient concentration and limitation, and the potential variation in P-buffering resulting from differences in catchment geology among rivers. Results of this research will be used as technical information for policy decision-making with respect to nutrient standards and controls for the Manawatu-Wanganui region.

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