



Effects of nutrient loading in Lake Brunner

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Nutrient status in Lake Brunner and effects of nutrient loading

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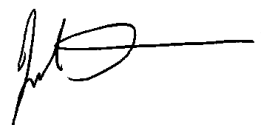
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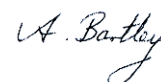
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Executive Summary

Lake Brunner is a large (41 km²), deep lake (maximum depth 109 m) in the northwestern part of the South Island. Its water quality is high and it is valued for its trout fishing. Development of dairy farms in the catchment has led to concern that its water quality will decline. This report examines changes in water quality since 1992 and the effects of nutrient loading from the catchment on nutrient status in the lake.

Lake Brunner is oligotrophic and algal productivity is very strongly limited by the availability of phosphorus, throughout the year, as indicated by nutrient ratios (N:P). Dissolved reactive phosphorus is almost absent as it is consumed immediately when it becomes available. There has been no apparent change in the level of P limitation since 1992.

Inflow rates were highest in June and October-November, at which time the mean total nitrogen (TN)/total phosphorus (TP) ratio in the tributaries was lowest, as a result of higher TP concentrations with increased flow rates. The lake retains 50 to 55% of phosphorus transported from the catchment by burial in the sediment and 30% of nitrogen is retained by burial or removed by denitrification.

Chlorophyll *a* (a measure of algal biomass) and epilimnetic (surface water) nutrient concentrations generally increased and Secchi depth (a measure of water clarity) decreased since the early 1990s, suggesting that land use may have deteriorated the water quality in the lake. Levels of dissolved reactive phosphorus used to be near or below detection limits but have increased since 1992. This report provides predicted values for chlorophyll *a*, algal biomass, primary productivity, and Secchi disk transparency, for a range of phosphorus loading rates.

The lake has a long residence time (1.14 year) which enhances the proportional retention of nutrients by the lake and therefore affects the relation between tributary nutrient loading and lake nutrient status. Because of an enhanced capacity for nutrient storage by burial in the sediment, lakes with long residence times are less sensitive to phosphorus loading and are more resilient than lakes that are flushed faster, on the condition that primary productivity does not exceed a level that could result in anoxia at the sediment/water interface. Lakes with long residence times that have moved beyond levels of nutrient loading that result in rates of algal productivity that cause anoxia in bottom waters will be very difficult to restore to a state with acceptable water quality.

Algal productivity was lowest in the cold season (August-September). At this time deep vertical mixing and internal loading resulted in increased epilimnetic concentrations of NO₃-N, which was not utilized by algae because of the growth limitation caused by low availability of phosphorus. Seasonal deep vertical mixing did not increase epilimnetic phosphorus concentrations, suggesting there is no larger reservoir of phosphorus in the hypolimnion, while there is for nitrogen.

The present volume weighted mean concentration of TP in the inflows is estimated at about 13 mg m^{-3} , slightly more than twice the concentration in the lake. Using a Vollenweider lake eutrophication model, phosphorus concentrations in the lake under a range of nutrient loadings are predicted based on residence time and retention efficacy. The critical mean phosphorus concentration in the lake inflows beyond which the lake is expected to become mesotrophic is 22.5 mg m^{-3} , about 1.7 times the present rate of phosphorus loading. Chlorophyll *a* concentrations are predicted to exceed 3 mg m^{-3} when the lake becomes mesotrophic and to exceed 7.5 mg m^{-3} when the lake becomes eutrophic.

Lake Brunner is vulnerable to changes in P loading, because of the large difference between the nitrogen and phosphorus concentrations relative to the stoichiometric demand of phytoplankton productivity. The three major streams draining dairy farms were lower in their TN/TP ratios (i.e., are more P-rich) than the other inflows and the lake waters and contribute 88% of the lake's total phosphorus load. Hence managing the phosphorus in the runoff from dairy farms is important for controlling algal productivity and the water quality of Lake Brunner.

It is recommended that hypolimnetic oxygen consumption and sediment P retention are monitored regularly during the period of stratified conditions to provide early warning of any lake deterioration towards the tipping point where stored P is released from the lake sediments due to bottom water oxygen depletion.

1. Introduction

Lake Brunner is the largest lake in the northwestern part of the South Island (Fig 1), with a surface area of 41 km². The lake is a popular tourist destination and is held in high esteem by trout fishermen. Lake Brunner is a deep lake (maximum depth 109 m, Spigel 2008), and while the lake is relative pristine, development of dairy farms in the catchment has lead to concern for its water quality. Presently about 20% of the catchment is used for agriculture (Rutherford et al. 2008). The report aims to summarise and analyse the existing information on the limnology of the lake to provide an improved information base for management decisions.



Figure 1: Lake Brunner, with the central lake sampling site indicated (NZMG coordinates: 2382561, 5840026).

More or less bi-monthly sampling of water quality has been carried out since 1992, with a gap between 1995 and 2001, by the West Coast Regional Council and by NIWA (Horrox 2008, Scarsbrook 2008; Chague-Goff 2008). This report examines

data from a site in the centre of the lake for trends in surface layer nutrient concentrations, water clarity, chlorophyll *a*, estimates nutrient retention by the lake, and discusses nutrient limitation in relation to levels associated with different trophic state classes and stoichiometric nutrient ratios for balanced algal growth. In addition, a model is presented that predicts phosphorus concentrations in the lake under a range of nutrient loadings and effects of increased nutrient loading on the lake ecosystem are discussed in terms of algal biomass, primary productivity and transparency.

This report complements research on the influence of management practices on dairy farms in the catchment on contaminant loadings to the lake (e.g., McDowell et al. 2008a, b). This information will contribute to development of a Bayesian Belief Network model to link land management and lake values as a scenario evaluation tool for use by managers.

2. Results and Discussion

2.1 Lake nutrient status

Secchi depth and epilimnetic concentrations of chlorophyll *a*, total nitrogen (TN), total phosphorus (TP), nitrate (NO₃-N) and dissolved reactive phosphorus (DRP) in Lake Brunner between 1992 and 2008 are in Figure 2 and averages are in Table 1. Total organic nitrogen (TON), calculated as TN – NO₃-N (more or less equivalent to PN + DON; NH₄ was ignored because it was not monitored before 2001 and NH₄ amounts on average to only 7% of dissolved inorganic nitrogen (DIN) in the mixed layer of Lake Brunner [J. Horrox personal communication]), consisted mostly of dissolved organic nitrogen (DON), while total organic phosphorus (TOP, calculated as TP – DRP), consisted mostly of particulate phosphorus (PP, Table 1).

The boundary between oligotrophic (generally nutrient poor and unproductive) and mesotrophic states in lakes is considered to be at 10 mg TP m⁻³, and 30 mg TP m⁻³ separates mesotrophic from eutrophic lakes (Vollenweider 1976; in Kalff 2003). Therefore on the basis of the average total phosphorus concentration Lake Brunner can be considered as oligotrophic. The average concentration nitrogen classifies Lake Brunner among oligotrophic lakes as well (Wetzel 2001), while the average Secchi depth places it at the boundary between mesotrophic and oligotrophic status (Wetzel 2001; Kalff 2003). The total phosphorus concentration is generally considered the most important of these indicators of trophic status. PO₄ recorded in March 1977 was lower than DRP since 1992, while TP recorded in March 1977 was much higher than since 1992 (Table 1). It seems likely that the TP concentrations reported for 1977 are erroneous.

Table 1: Mean epilimnetic nutrient¹ and chlorophyll *a* concentrations (mg m⁻³), Secchi transparency (m), turbidity (NTU), total suspended solids (g m⁻³), and nutrient ratios (mol mol⁻¹), in 25 m integrated tube samples. March 1977 data are from Paerl et al. (1979) from mixed layer and 30 m integrated tube samples.

	1992-1995	2001-2008	1992-2008	March 1977
TN	146.2	194.0	176.9	
TP	5.1	6.1	5.7	22.6-26.6
TN/TP	63.2	70.2	68.8	
Chlorophyll <i>a</i>	1.1	1.4	1.3	1.54-3.56
Secchi depth	6.3	5.2	5.8	5.5
TSS		14.7		
TURB		5.3		
NH ₄ -N		5.8		0.4-0.5
NO ₃ -N	66.4	95.7	84.5	68.7-87.0
DRP	0.4	0.8	0.6	0-0.2
NO ₃ /DRP	362	269	297	
TDN		169.7		
TDP		2.6		
TDN/TDP		145.6		
DON		68.2		19-22
DOP		1.8		0.9-1.0
DON/DOP		82.8		25.6
PN		25.7		
PP		3.7		
PN/PP		15.5		
TON (TN-NO ₃)	77.8	98.3	91.0	
TOP (TP-DRP)	4.7	5.3	5.1	
TON/TOP	36.5	40.8	39.7	

¹ Abbreviations: TN and TP = total N and P; TSS = total suspended solids; TURB = turbidity; DRP = dissolved reactive P; TDN and TDP = total dissolved N and P; DON and DOP = dissolved organic N and P; PN and PP = particulate N and P; TON and TOP = total organic N and P.

2.2 Interannual trends in nutrient levels and productivity proxies

Chlorophyll *a* and epilimnetic nutrient concentrations have generally increased since the early 1990s (Fig. 2), and there has been a corresponding decrease in Secchi depth. TN was 33% higher in 2001-2008 compared with 1992-1995 while TP increased 19%. The increase in TN since the 1990s (Fig. 2) was explained in similar proportions by the increase in TON and in NO₃-N (Fig.3; Table 1). TOP increased and its proportion of TP slightly decreased. Levels of dissolved reactive phosphorus used to be near or below detection limits but have increased. The DRP fraction of TP was very small (Fig 3). While TOP was for a large part contained in particulate matter, TON was predominantly dissolved organic nitrogen.

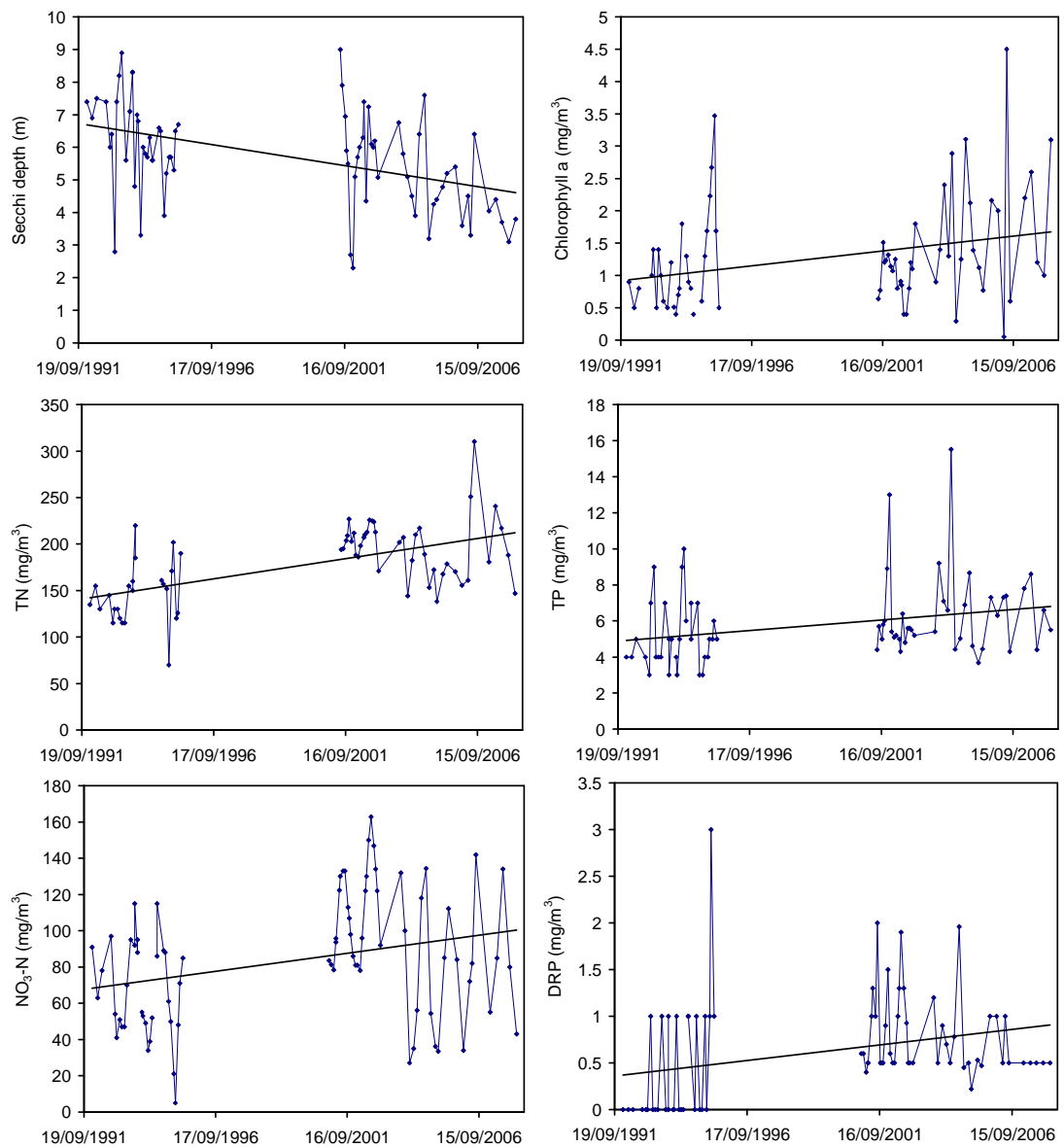


Figure 2: Trends since the 1990s in Secchi depth, chlorophyll *a*, and concentrations of total nitrogen, total phosphorus, nitrate (NO₃-N) and dissolved reactive phosphorus (DRP) in the upper 25 m (integrated samples).

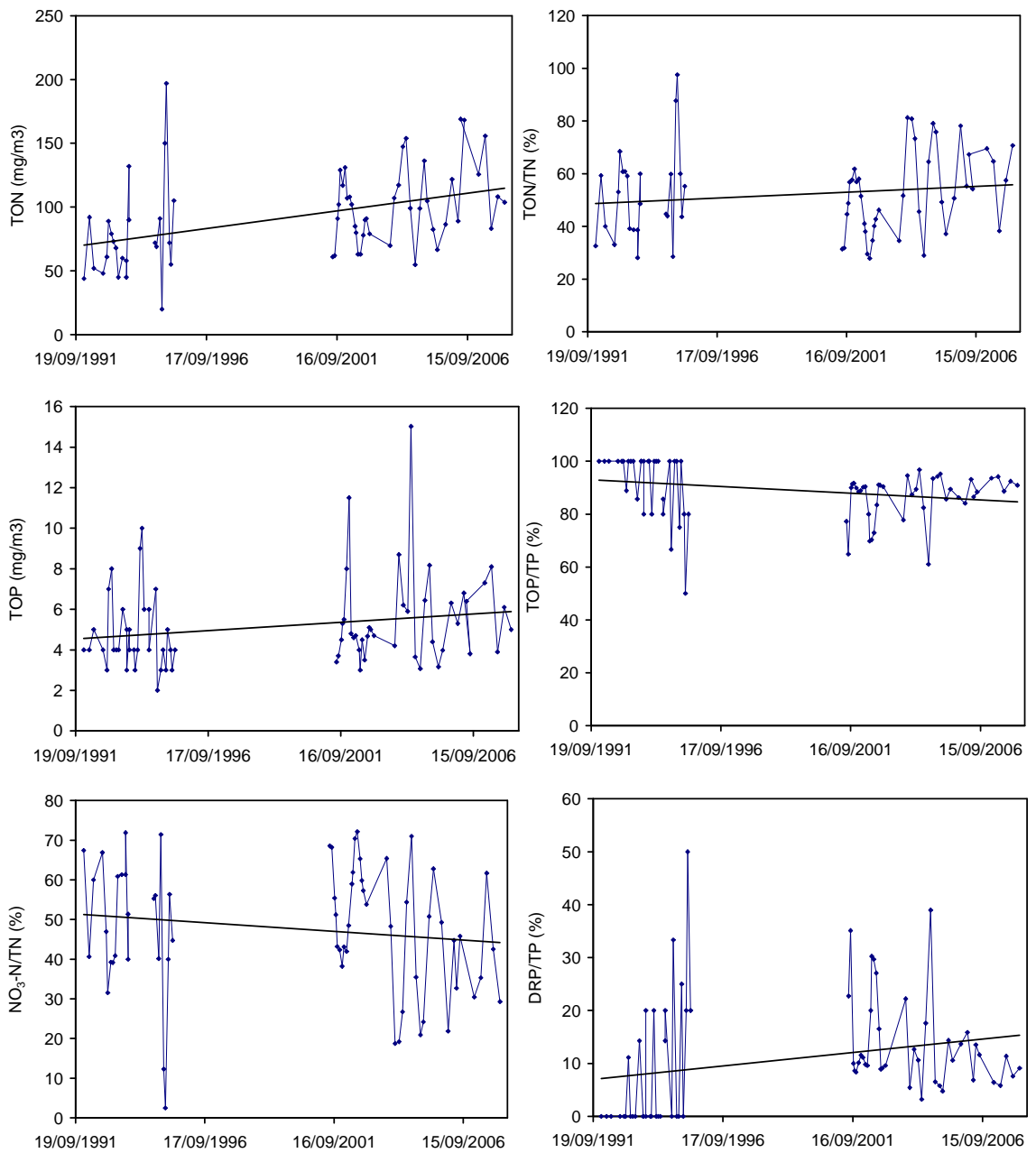


Figure 3: Trends since the 1990s in the composition of total nitrogen and phosphorus in the upper 25 m (integrated samples).

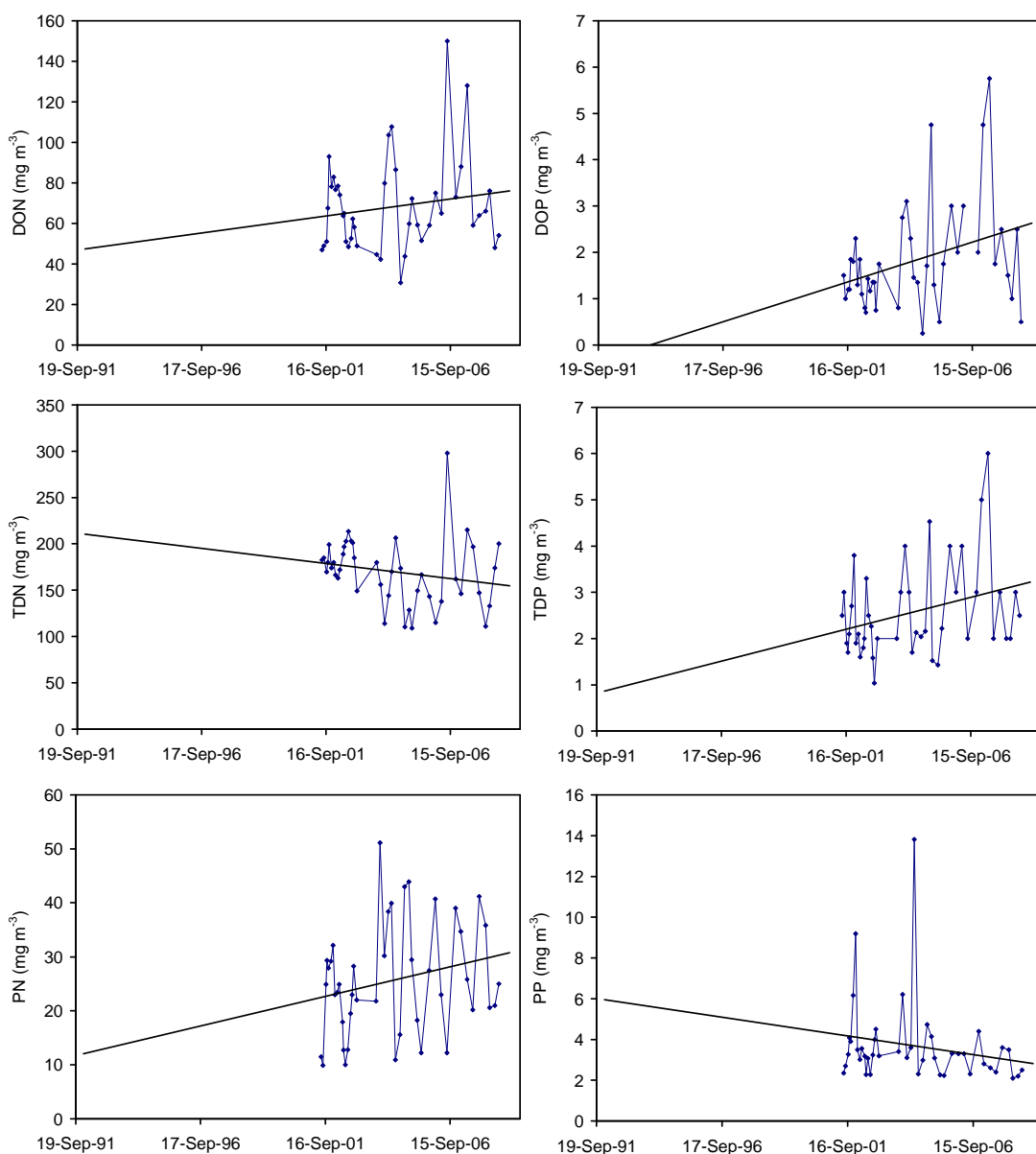


Figure 3: (cont.)

The trends of decreasing secchi disk transparency and increasing chlorophyll *a* concentrations, were earlier reported by Horrox (2008), Scarsbrook (2008) and by Chague-Goff (2008) and may indicate increased eutrophication resulting from increased loading of phosphorus and nitrogen. On the other hand, Pearl et al. (1979) reported a chlorophyll *a* concentration of 1.54 mg/m³ (in a 30 m integrated tube sample; the mixed layer value was higher: Table 1) and a Secchi depth of 5.5 m in March 1976, similar to recent values. While the data of Paerl et al. (1979) do not

provide evidence for a substantial change in the lake's pelagic ecosystem in the past 30 years, they represent single measurements and may not be representative for the earlier state of the lake. In addition, while the bottom depth at the 1977 sampling site was >50m, it may not have been sufficiently offshore to prevent effects related to the higher productivity found at near shore locations and bays (Horrox 2008; see also the high TP concentrations reported in 1997, Table 1).

2.3 Relationships between nutrients, chlorophyll *a* and Secchi depth

There were weak but significant negative relations between the concentration of TP in the centre station of the lake and Secchi depth ($R^2 = 0.26$, $P < 0.0001$, $n = 72$), and between the concentration of TP and chlorophyll *a* (a measure of the biomass of algal biomass; $R^2 = 0.11$, $P < 0.005$, $n = 71$). There was no statistically significant relation between the concentration of TN and Secchi depth ($R^2 = 0.009$, $P = 0.46$, $n = 64$) or chlorophyll *a* ($R^2 = 0.01$, $P = 0.37$, $n = 65$). The relation between Secchi depth and chlorophyll *a* was statistically significant, but rather weak ($R^2 = 0.24$, $P < 0.0001$, $n = 62$). This indicates that water clarity (Secchi depth) is also influenced by other factors, such as humic material and inorganic suspended solids from the catchment.

There were no statistically significant relationships between concentrations of DRP with either Secchi depth or chlorophyll *a*. There was a significant negative relation between the concentrations of $\text{NO}_3\text{-N}$ and chlorophyll *a* ($R^2 = 0.21$, $P < 0.0005$, $n = 66$), and a weaker positive relation for $\text{NO}_3\text{-N}$ and Secchi depth ($R^2 = 0.10$, $P < 0.01$, $n = 72$). The relationships between $\text{NO}_3\text{-N}$ and these measures of algal biomass suggest that NO_3 accumulates when productivity decreases. Uptake of dissolved phosphorus is likely to be very rapid and concentrations of dissolved phosphorus were very low, near detection limits, although increasing slightly since 1992.

TN and TP were not significantly related ($P > 0.05$), suggesting a strong disconnection between the uptake rates of N and P relative to availability, resulting from strong P limitation and excess availability of nitrogen. There was a significant correlation between $\text{NO}_3\text{-N}$ and TN ($R^2 = 0.34$, $P < 0.0001$, $n = 64$), and a weakly significant relation between DRP and TN ($R^2 = 0.06$, $P < 0.05$, $n = 64$) but not between DRP and TP ($P > 0.05$, $n = 72$).

2.4 Nutrient ratios

The ratio of mean N: mean P (all ratios are given as molar ratios) in particulate matter was 16, exactly the same as the Redfield ratio expected in phytoplankton. Non-particulate N:P ratios were very high in the lake's epilimnion, an average 40 for TON/TP (the ratio of the organic fractions of nitrogen and phosphorus respectively, Fig. 4), 69 for TN/TP and as high as between 200 and 400 for NO₃/DRP, not including data when DRP was below detection, suggesting very strong P limitation. Arithmetic means of nutrient ratios in individual sampling occasions, while higher than these ratios of means, are not appropriate, especially when the concentration of DRP is near detection limits. For comparison, in more nitrogen limited lake Taupo epilimnetic TON/TP, PN/PP, TN/TP and NO₃/DRP ratios are 34, 20, 28 and only 1.6 respectively (measured in 2003-2007; calculated from data in Gibbs 2008). The N:P ratios in Lake Brunner were variable between sampling occasions but there was no significant trend between 1992 and 2008 ($R^2 = 0.006$ for TN/TP and $R^2 = 0.06$ for NO₃-N/DRP, $P > 0.05$; Fig. 4). Lakes with residence times > 0.5 y like lake Brunner (1.2 y, see below) often have TN:TP ratios > 30 (Wetzel 2001). Lakes with long residence times typically have TN:TP ratios that are higher than in the inflows because of high rates of retention of P (Wetzel 2001). NO₃-N was on average 48% of TN while DRP was only 11% of TP, further suggesting P limitation.

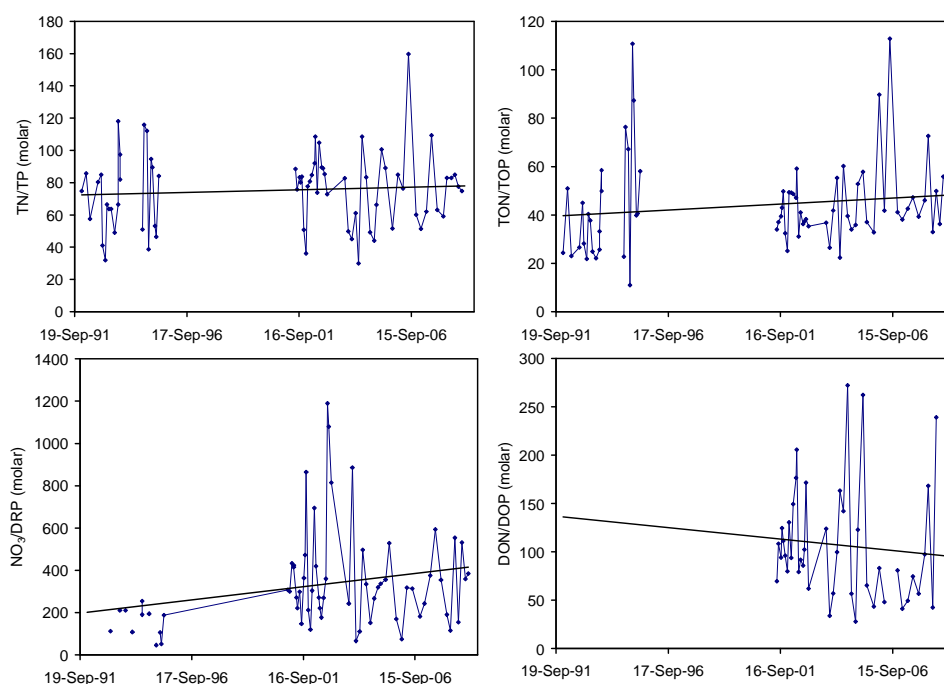


Figure 4: Molar ratios of N and P in Lake Brunner, in integrated water samples between 0 and 25 m depth.

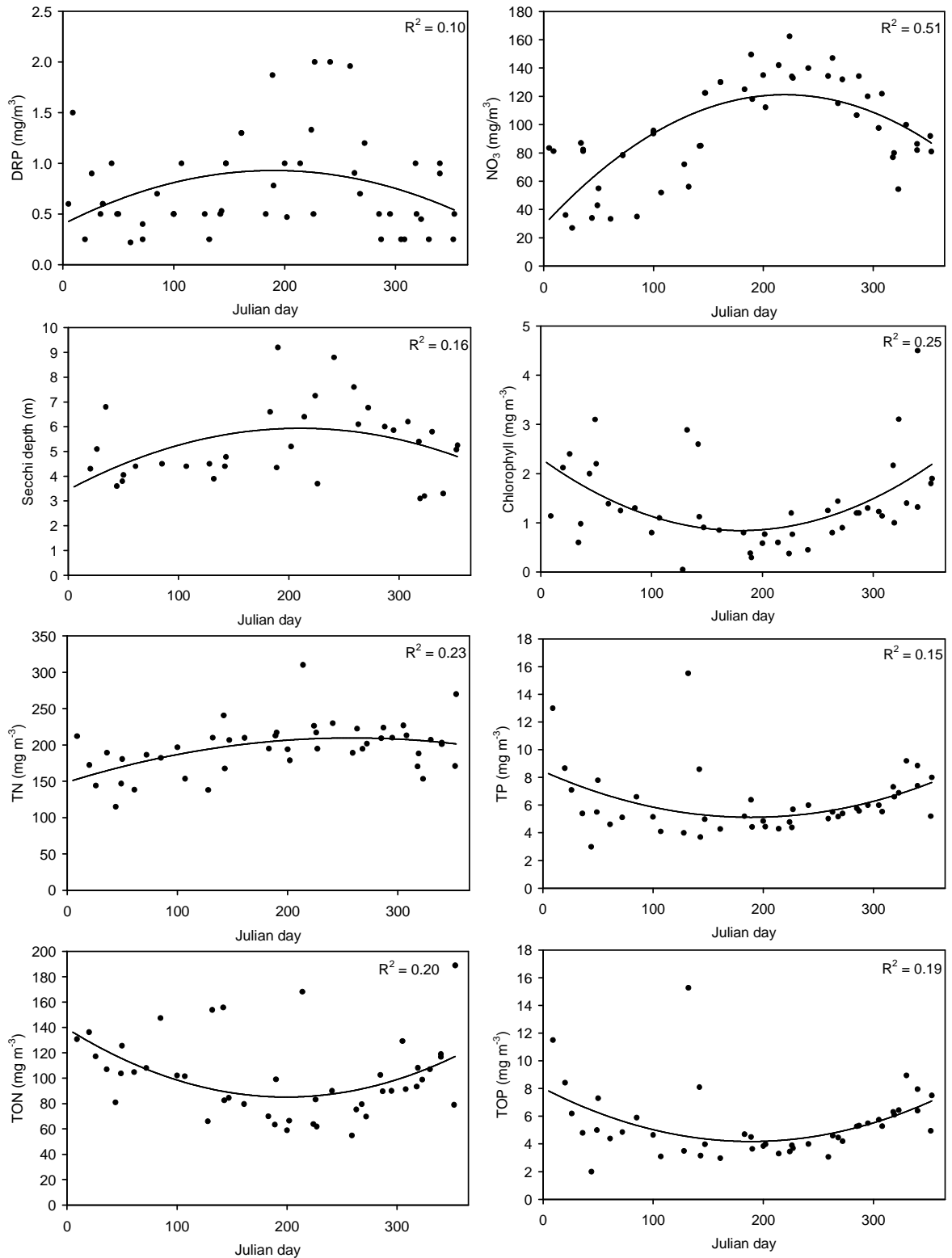


Figure 5: Epilimnetic seasonality for day of the year, with second order polynomial fits. Only data since 2001 are used, to decrease the effect of the trends between years.

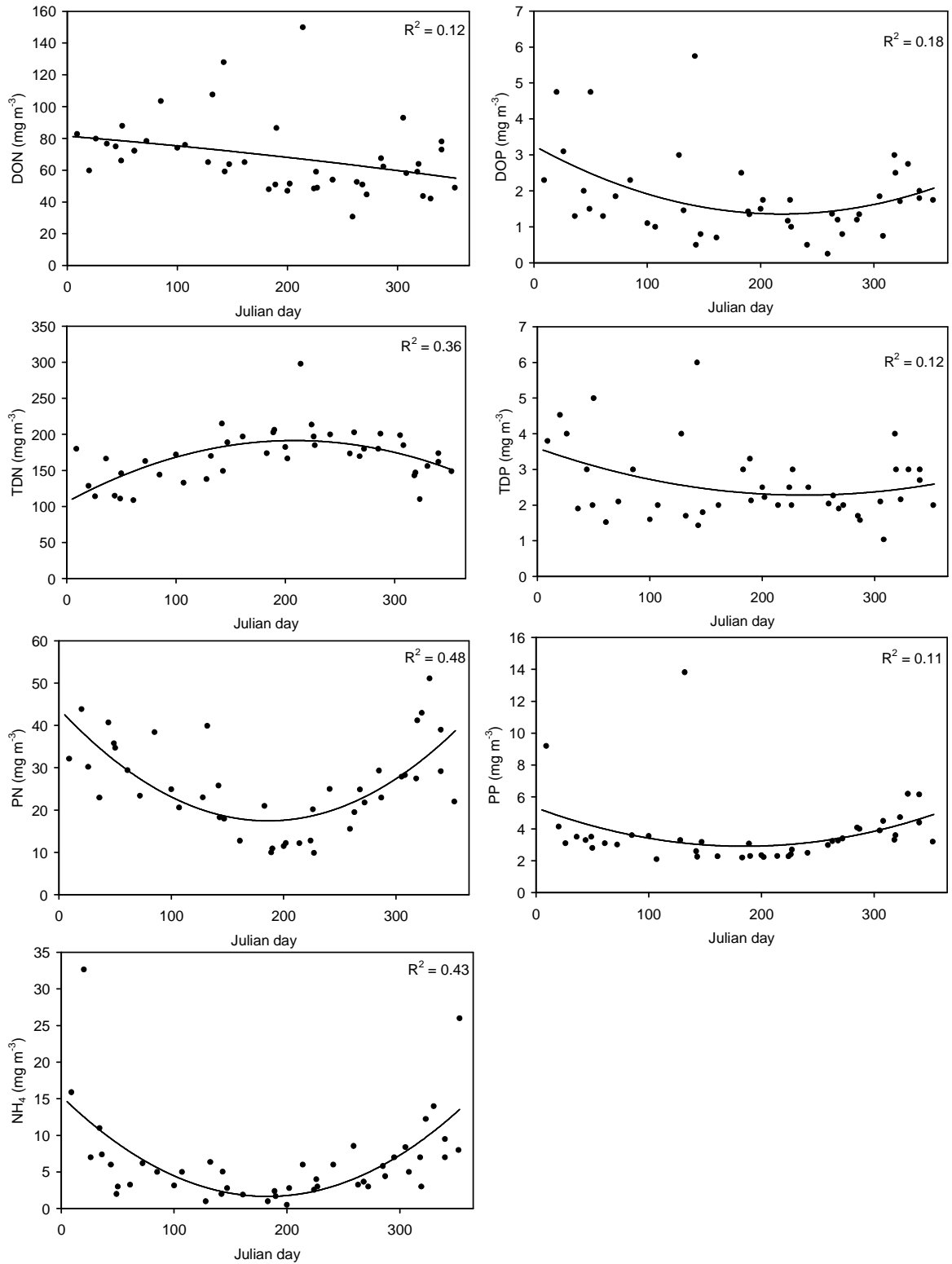


Figure 5: (cont.)

2.5 Seasonality

Productivity was lowest in the winter as indicated by a maximum in Secchi depth and by minima in chlorophyll *a*, PP and PN (Fig. 5). In the cold season (August-September, days 213-274) when deep vertical mixing occurs (Spigel 2008), epilimnetic NO₃-N was markedly elevated, suggesting upwelling and strong internal loading by recharge from the hypolimnetic reservoir. DRP was also higher at this time but the trend was less clear. TN increased slightly in winter. There was no clear trend in TON, while there was a decrease in TP and TOP in the winter months. The winter time NO₃-N maximum has increased since the early 1990s (Burns and Rutherford 1998).

These results suggest that while the hypolimnion and upwelling is an important source for NO₃-N, it is not for phosphorus. The seasonality of NO₃-N and TP suggests that NO₃-N is higher in the hypolimnion than in the epilimnion while the opposite is the case for TP, probably as a result of efficient P retention in the sediment with well oxygenated bottom waters. Phosphorus loading in Lake Brunner is predominantly through external sources, from the catchment, which explains why upwelling from the hypolimnion does not enhance productivity. In this it differs for instance from Lake Taupo (Gibbs 2008), another similarly deep lake where in contrast productivity is greatest in the cool months of August and September, driven by deep mixing and partial overturn of the water column. Lake Brunner is similar to Lake Waikaremoana with respect to its phosphorus limited productivity and the seasonal dynamics of nutrient cycling and productivity (Vincent 1983).

Ammonia which is released when algae decompose is quickly oxidized when oxygen concentrations are high. Its concentration does not increase with depth in fall and in spring, and it shows a marked decrease in the epilimnion during the unproductive winter season (Fig. 5), unlike nitrate.

Higher DIN concentrations in the hypolimnion compared with the epilimnion, and the opposite case for PO₄ and TP (higher in the epilimnion), were reported to occur in March 1976 in Lake Brunner (Paerl et al. 1979) which agrees with the results presented here. In 1976 each of these differences between hypolimnetic and epilimnetic concentrations was more than two fold. In 1992-1995 the differences in NO₃-N, DRP and TP between the hypolimnion and epilimnion were between one and two fold (Burns and Rutherford 1998). In the fall, just before the annual turnover during 2003-2008, NO₃-N concentrations near the bottom were up to 3 times higher than near the surface (depth profile data are not presented here). In 2003-2008 there

were no consistent differences in concentrations of DRP, TDP, DOP, TP or in DON with depth. TN/TP was 71% higher at 90 m compared with 10 m depth in the fall at the end of the stratified season, while only 9% higher in spring, suggesting accumulation of NO₃-N in the hypolimnion but not of phosphorus during the stratified season.

The epilimnetic concentration of TP, which is mostly in the form of TOP, decreases in winter, perhaps because it gets mixed downwards. In addition, in July-August phosphorus loading from the catchment is at its lowest (see section 2.9), contributing to an explanation for a lower epilimnetic concentration of TP at this time. However, the contribution of the concentration of TP in the inflows to the explanation of a higher epilimnetic TN/TP ratio in August-September (Fig. 6) must be minor because TN loading is at its lowest at this time as well (section 2.9), which is not reflected in epilimnetic concentrations (Fig. 5). The seasonal plots (Fig. 5) explain the absence of correlation between epilimnetic TN and TP (section 2.3).

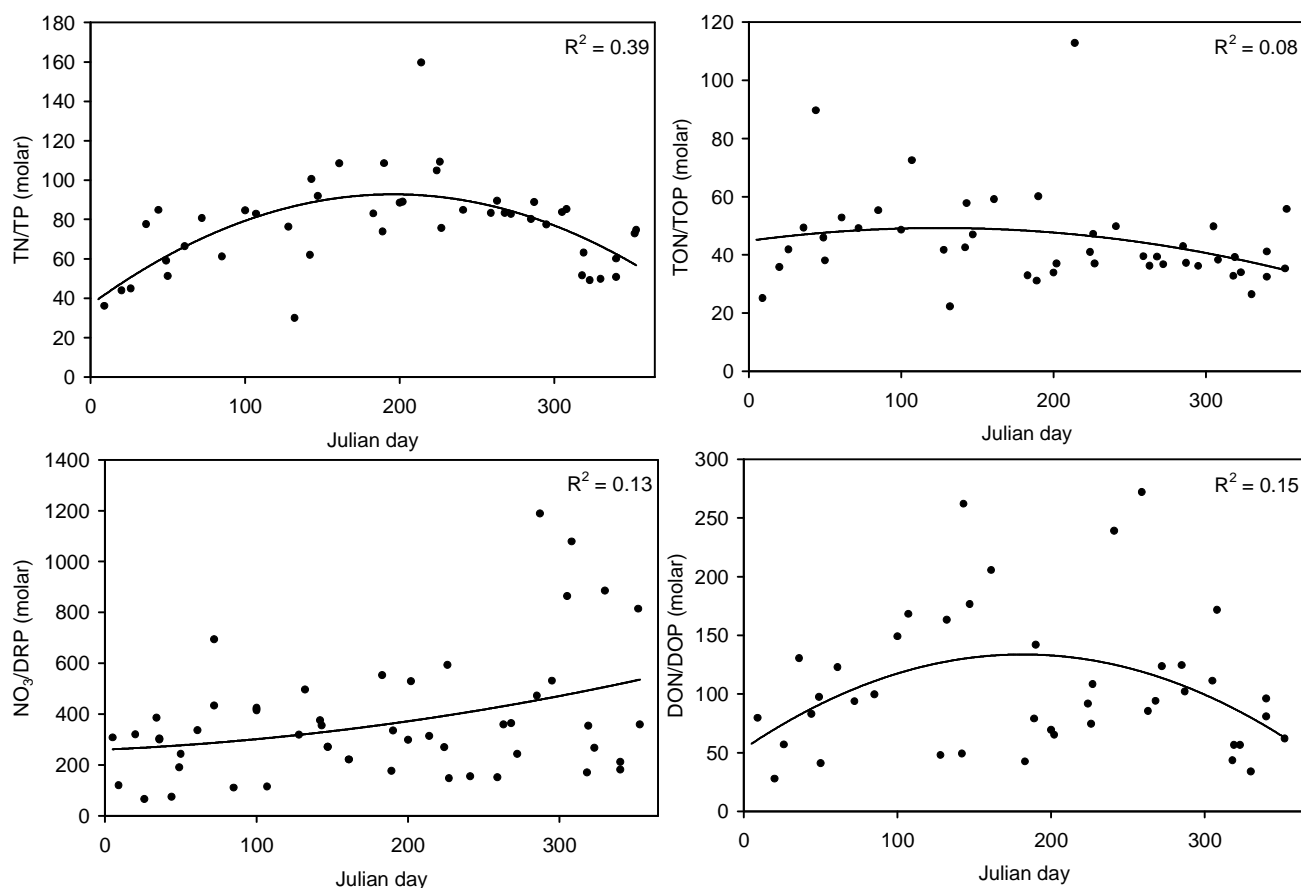


Figure 6: Epilimnetic ratios of forms of N and P in 2001-2008 sorted for day of the year.

Phosphorus limitation is considered severe when organic N:P > 23 (Wetzel 2001). In Lake Brunner organic N:P was never found lower than 23 and was on average almost twice as high, 43 in 1992-1995 and the same in 2000-2008. Dissolved organic nutrients are not always available for assimilation by phytoplankton. The mean ratio TN-DON/TP-DOP, the metric recommended in Pridmore (1987) to evaluate nutrient limitation, was 65, and was only twice below 33 in 2001-2008 (n = 44), the value which, when exceeded, suggests P limitation. Paerl et al. (1979) suggested P limitation in Lake Brunner, based on a single day of measurements of P and N. The absence of correlation between TN and Secchi depth, between concentrations of TN and TP, and the accumulation of NO₃-N when algal productivity decreased, are effects of phosphorus limitation and excess availability of nitrogen. The data presented here provide strong evidence that phosphorus is severely limiting primary production throughout the year in Lake Brunner (Fig. 6).

2.6 Water balance

Evaporation (E) at Lake Brunner, extrapolated from Penman open water evaporation at Weymouth (NIWA CliFlo climate data base, 27 km distance from the center of Lake Brunner and the nearest site for which evaporation data are available) is estimated to be 909 mm per year. This amounts to a rate of 1.18 m³ s⁻¹ over the full lake area (at Lake Brunner a 1 m lake level change per year in water balance components is equivalent to a flow rate of 1.3 m³ s⁻¹). Because the annual mean outflow rate (O) is 61.5 m³ s⁻¹ (Rutherford et al. 2008) the mean total loss of water (E + O) is 62.7 m³ s⁻¹. Evaporation is only 1.9% of the total water balance of Lake Brunner.

Mean annual rainfall (R) on the lake computed from Te Kinga (2006), Arnold Power Station (1940-1994), Mitchells (1988-1993) and Inchbonnie for 1940-2006 (NIWA CliFlo climate data base) is 3784 mm, amounting to a mean flow rate of 4.93 m³ s⁻¹. Rainfall contributes 7.9% of the annual water budget. Mean annual total input of water to the lake by rivers & groundwater is:

$$I = O + E - R = 57.8 \text{ m}^3 \text{ s}^{-1}$$

Therefore, the volume of water that is considered to contain the nutrients transported from the catchment to the lake is 57.8 m³ s⁻¹ (Table 2). In the calculations of P loading the effect of the proportion of nutrients entering the lake from the atmosphere (rainfall + dryfall directly on the lake) is ignored. There are no data on atmospheric nutrients inputs to the lake and they are expected to be small relative to the catchment inputs.

Table 2: Hydrological data used in the calculations of P loading.

Inflow rate	$57.76 \text{ m}^3 \text{ s}^{-1}$
Outflow rate	$61.50 \text{ m}^3 \text{ s}^{-1}$
Catchment area (C)	440 km^2
Lake area (A)	41.1 km^2 (Spigel 2008)
Catchment excluding lake area	398.9 km^2
Mean depth (\bar{z})	55.03 m
Volume (V)	$2.260572 \times 10^9 \text{ m}^3$ (Spigel 2008)
Water discharge height (q_s)	$= \bar{z} / T_w = (O+E)/A = 48.16 \text{ m y}^{-1}$
Hydraulic residence time (T_w)	$= V / (E + O) = 1.14 \text{ year.}$

There was no strong seasonality to tributary inflow rates (Fig. 7). Mean monthly flow was about $50 \text{ m}^3 \text{ s}^{-1}$ most of the year, with higher flows in June and October-November.

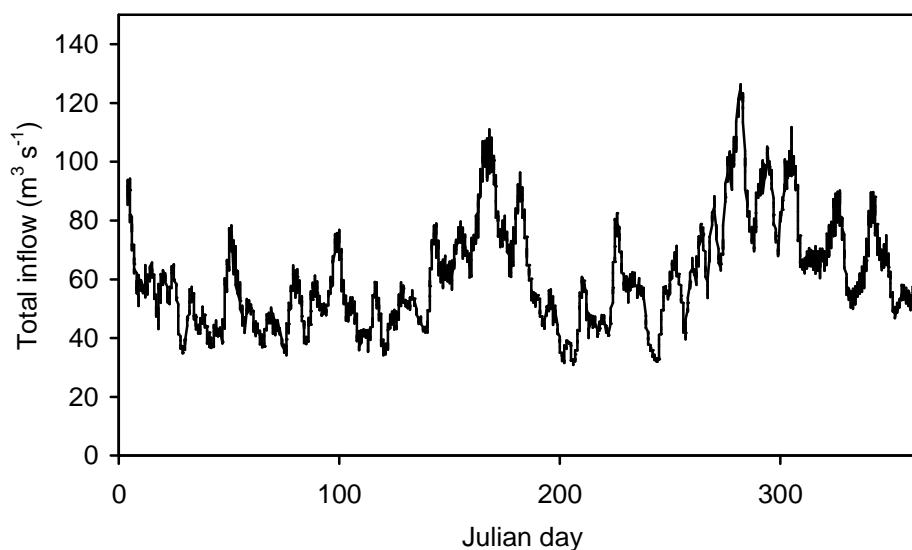


Figure 7: Thirty-day moving average of total tributary inflows for 1998-2007, sorted for day of the year (based on data prepared by Rutherford et al. 2008).

2.7 Nutrient loading

When nutrient concentrations in the inflow are the same as in the lake, the catchment loadings can be derived from the concentrations of TN and TP in the lake times the inflow rate:

$$\begin{aligned} \text{Nitrogen} & \quad 190 \text{ mg m}^{-3} \times 57.8 \text{ m}^3 \text{ s}^{-1} = 10.98 \text{ g s}^{-1} = 346.3 \text{ ton y}^{-1} = 8.69 \text{ kg ha}^{-1} \text{ y}^{-1} \\ \text{Phosphorus} & \quad 5.8 \text{ mg m}^{-3} \times 57.8 \text{ m}^3 \text{ s}^{-1} = 0.33 \text{ g s}^{-1} = 10.6 \text{ ton y}^{-1} = 0.27 \text{ kg ha}^{-1} \text{ y}^{-1} \end{aligned}$$

However, because of the losses of N and P in the lake by denitrification and burial actual catchment loadings are higher, and the difference indicates the proportion of nutrients retained or removed in the lake.

The stoichiometric TN / TP ratio in the lake's epilimnion is 69 (mol mol^{-1}), higher than TN / TP ratios found in streams, suggesting they transport more P than is present in the lake's upper water column (relative to N).

The present mean phosphorus concentration in the inflows can be estimated from the concentration in the lake ($[\text{P}]_{\text{lake}}$) and the residence time, as

$$[\text{P}]_{\text{inflow}} = [\text{P}]_{\text{lake}} \times (1 + \sqrt{T_w}) = 6 \times (1 + \sqrt{1.14}) = 12.5 \text{ mg m}^{-3}$$

(Kalf, 2003). From the Vollenweider equations (Fig. 8) a similar present mean concentration of TP in the tributaries of 13.5 mg m^{-3} follows. This concentration compares well with the mean concentrations in the following rivers: Crooked, Poerua (part of the Crooked system), and Orangipuku (Rutherford et al. 2008), which are the major river systems that drain dairy farmland in the Lake Brunner catchment.

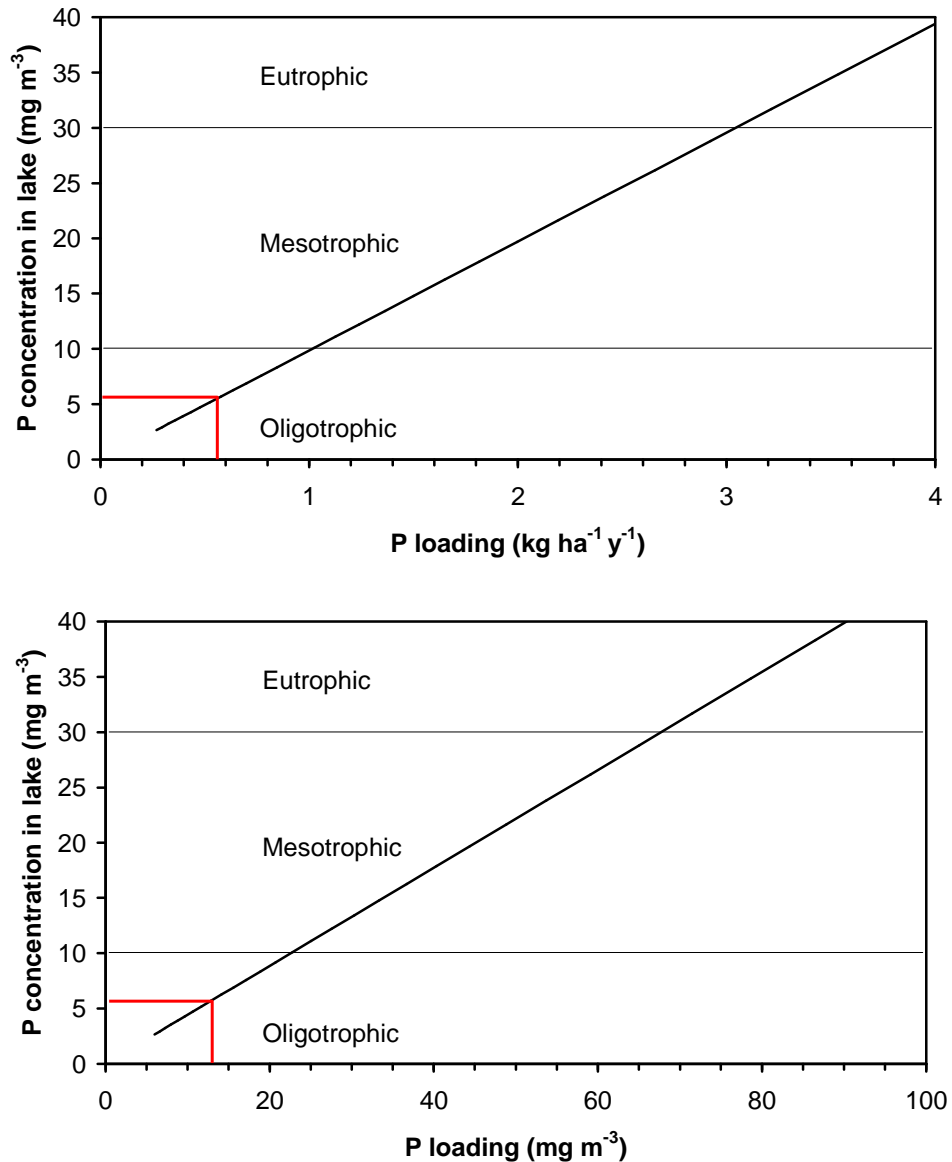


Figure 8: Vollenweider relationships (Kalff 2003) between TP loading from Lake Brunner's catchment (in kg per hectare land area per year, upper panel, and in the mean concentration of P in the inflows, lower panel) and expected concentrations of TP in the lake. Critical levels of P concentrations dividing trophic states are indicated by horizontal lines. The red line indicates the present situation in the lake.

The relationship between phosphorus concentration in the lake (P) and the loading rate (Fig. 8) is given by

$$[P]_{\text{lake}} = \frac{L_p / q_s}{(1 + \sqrt{T_w})}$$

where the loading rate of phosphorus per area of the lake surface L_p is equal to

$$L_p = I A^{-1} [P]_{\text{inflow}}$$

the mean concentration in the inflows times the flow rate, divided by the lake area.

A mean concentration of TP in the inflows of 12.5 - 13.5 mg m⁻³ amounts to a loading rate per area of the catchment (land only) of 0.56 - 0.61 kg ha⁻¹ y⁻¹. This compares well with the mean yield for TP of 0.54 kg ha⁻¹ y⁻¹ for the whole catchment estimated by tributary monitoring (Rutherford et al. 2008). The value of Rutherford et al. (2008) amounts to 0.59 kg ha⁻¹ y⁻¹ when considered as loading rate per unit area of the land surface in the catchment, and is therefore within the range of the estimates presented here.

The critical loading (L_c) in terms of mean phosphorus concentrations in the inflow beyond which the lake is expected to become mesotrophic is (adapted from equations in Kalff 2003):

$$L_c = \frac{10q_s A(1 + \sqrt{T_w})}{31557600I} = 22.5 \text{ mg m}^{-3}$$

which is equivalent to 1.03 kg ha⁻¹ y⁻¹ per unit land area in the catchment (31,557,600 is the number of seconds in an average year). This is about 1.7 times the present rate of phosphorus loading.

The time for a new equilibrium concentration of phosphorus to become established following changes in loading rates can be estimated by (Kalff 2003):

$$t(95\%) = 3 T_w (1 - R) = 1.57 \text{ year}$$

where t (95%) = time for reaching 95% of the equilibrium concentration, and $R = 0.54$ = the annual fractional retention of phosphorus (see section 2.8). For nitrogen t (95%) would be 2.56 year as a result of lower retention of nitrogen (section 2.8).

Vollenweider relations between TP concentrations in inflows and in the lake are based on the assumption of fully oxygenated bottom waters. In lakes where part or all of the bottom temporarily or permanently becomes anoxic, the method fails and TP concentrations in the lake are underestimated. When external P loading increases past a “tipping” point where low oxygen conditions start to develop in bottom waters by sedimentation of organic matter, a smaller proportion of P will be permanently buried and additional inputs to the water column of dissolved phosphorus will appear through release of P from the sediments. As a result, the Vollenweider method will underestimate P concentration in the lake when productivity exceeds a certain threshold that results in reduced oxygenation of bottom water (Nurnberg 1984). A deep lake like Lake Brunner is relatively resilient to increased phosphorus loading, however, once the lake is beyond this threshold remediation in this lake will be relatively difficult.

Lake Brunner is sensitive to any increase in P because of the large difference between the nitrogen and phosphorus concentrations, with a high N:P ratio relative to the average stoichiometric demand (16:1) of phytoplankton for productivity (Wetzel 2001). A very swift response to P loading is expected by increased growth rates of phytoplankton which will rapidly assimilate the phosphorus entering the lake.

While Flint (1975; in Paerl et al. 1979) reported *anabaena* in Lake Brunner, Paerl et al. 1979 found no cyanophytes and found diatoms dominated the phytoplankton biomass. While the present low phosphorus concentration probably prevents the occurrence of blooms of cyanobacteria in Lake Brunner, a faster increase in P loading compared with N loading may result in conditions that are more favourable for cyanobacteria.

2.8 Nutrient retention

The fraction of P that is retained by lakes is expected to decrease with increased loading and to increase with the residence time (Kalff 2003; Wetzel 2001). Predicted retention of P by burial is (Fig. 9):

$$R = \sqrt{T_w} (1 + \sqrt{T_w})^{-1} = 52\% \quad (\text{adapted from Kalff, 2003})$$

with T_w is water residence time = 1.14 y. Therefore, roughly half of P loaded to the lake may get buried in the lake sediment. The amount of phosphorus that leaves the lake by the outflow (ton year⁻¹) as predicted by the Vollenweider equations is 47% of the total P loading to the lake, suggesting that 53% is being retained in the lake. The predicted 52 to 53% retention of P agrees closely with the ratio of $[P]_{\text{lake}} / [P]_{\text{inflow}}$ that follows from the Vollenweider equations (Fig. 8), 45%, which suggests that 55% is being retained in the lake (ignoring a relative small dilution by rainfall and concentration by evaporation in the lake). The retention of P estimated from independent estimated and partly observed data (catchment yield 0.54 kg P ha⁻¹ y⁻¹ [Rutherford et al. 2008] and the mean epilimnetic concentration of TP for 1992-2008 multiplied by the outflow rate) is 53%, identical to the retention estimated from data generated by the Vollenweider model. The estimate for retention of P decreases to 50% when using the mean epilimnetic concentration of TP for 2001-2008 (6.1 g m⁻³).

On average lakes retain about 25% of input P (Wetzel 2001), and larger proportions in deep and fully oxygenated lakes like Lake Brunner. The fact that the observed retention of phosphorus, as derived from observed $[P]_{\text{lake}}$ and from the P loading rate, is similar to the predicted retention suggests that internal loading of phosphorus is negligible in Lake Brunner (Nurnberg 1984). It follows that oxygen concentrations in bottom waters do not drop below levels sufficient to allow noticeable phosphorus release from the sediment. This conclusion agrees with phosphorus concentrations not increasing with depth in the hypolimnion, while total nitrogen concentrations do increase with depth (data personal communication J. Horrox).

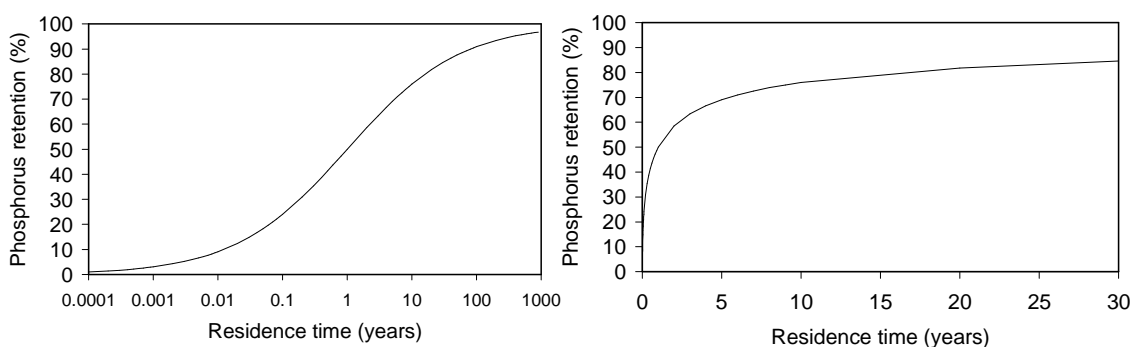


Figure 9: The general expected relationship between residence time and efficiency of phosphorus retention, for two different scales of residence time. Note logarithmic axis for residence time in left panel.

Nutrient ratios supply an additional indication of strong P retention in Lake Brunner. TN/TP ratios were lower in the inflows than in the lake. While TN/TP was an average 69 mol mol⁻¹ in the lake, N and P yields from the catchment were 11.3 and 0.54 kg ha⁻¹ yr⁻¹ respectively (Rutherford et al. 2008), from which an inflow TN/TP ratio follows of 46 mol mol⁻¹. The three main dairy farm draining streams had lower TN/TP ratios with a volume weighted mean of 35 mol mol⁻¹. These three rivers (Crooked, Hohonu and Orangipuku) drain 42.7 m³ s⁻¹ to the lake out of a total inflow of 57.9 m³ s⁻¹ (74%), and together advect to the lake 19.06 ton P per year out of a total P load to the lake of 21.5 ton (88%) and 299 ton N per year out of a total N load of 451 ton (66%; calculated from data in Rutherford et al. 2008). The dairy streams therefore discharge relatively more P into the lake, compared with N, than the remainder of the lake's catchment.

A TN/TP ratio in the lake of 98 would follow from an inflow TN/TP ratio of 46 mol mol⁻¹, if 53% of P is retained. Instead the lake TN/TP ratio is 69, suggesting that 30% of nitrogen is retained. This estimated 30% retention of nitrogen by the lake includes the effects of loss of fixed nitrogen by denitrification, and by permanent burial in the sediment. The lake retains a smaller proportion of nitrogen than of phosphorus. In lakes with oxic hypolimnia the retention of P is much more efficient than the retention of N. In lakes with oxygenated bottom waters phosphorus binds to clays and aluminium, iron, manganese and carbonates and precipitates from the water column more readily than nitrogen, resulting in higher burial rates and in a larger proportion of retained phosphorus compared with nitrogen. This is the case in particular in lakes with long residence times which allow more time for sedimentation from the epilimnion. In lakes where bottom water has become anoxic, such as in highly eutrophic lakes, the process is reversed and not only is the phosphorus binding capacity reduced but previously buried phosphorus can be mineralised and released from the sediments, potentially resulting in a negative retention (Nurnberg 1984) and phosphorus concentrations that are higher than in the inflows. In such lakes with anoxic bottom waters a positive feedback process may further enhance primary productivity, algal growth and blooms. Decomposing remains of algal blooms maintain or increase the anoxia in bottom waters, perhaps interrupted only when the lake overturns and mixes fully during winter, during which the bottom waters are reoxygenated.

The lake nutrient data (and therefore their ratios) are based on sampling in the upper 25 m, which is generally within the upper mixed layer. Evidence is available that the higher TN/TP ratios in the upper mixed layer compared with the inflows are not

explained by lower TN/TP ratios in the hypolimnion. The TN/TP ratio in surface water (Fig. 6) increases during deep mixing and overturn in the winter, suggesting that TN/TP in deep water may be even higher than in the surface layer. This is supported by measurements in March 1977 (Paerl et al. 1979) which showed an epilimnetic NO₃/TP ratio of 5.7 (TN not available) and a hypolimnetic NO₃/TP ratio of 24. In addition, full water column profile data collected biannually since 2003 in autumn (May) and in Spring (September to December; personal communication J. Horrox) show TN concentrations increasing with depth while TP does not increase with depth or decreases. Therefore, the difference in retention proportions of nitrogen and phosphorus are real and the ‘missing’ phosphorus or excess nitrogen cannot be explained by lower TN/TP ratios in the hypolimnion.

Lakes with long residence times (> 6 months) typically have N/P ratios higher than the mean in the inflows (Wetzel 2001) suggesting that in such lakes retention of phosphorus is expected to be more efficient than retention of nitrogen. The estimated 30% retention of nitrogen in Lake Brunner is only slightly lower than the average 34% retention of nitrogen found in lakes (Saunders and Kalff 2001) and it agrees closely with the predicted retention using an equation of Harrison et al. (2009) for nitrogen removal in lakes:

$$R = 1 - 10^{\frac{-6.83T_w}{z}} = 28\%$$

Nitrogen retention increases with water residence time (Windolf et al. 1996). In lakes about two thirds of nitrogen retention is accounted for by denitrification and the remainder by sedimentation and uptake by aquatic plants (Saunders and Kalff 2001).

2.9 Nutrient ratios in inflowing rivers

Flow weighted TN/TP ratios for the Poerua, Crooked, Hohonu, Carew and Orangipuku rivers were 23, 33, 57, 58, and 66 mol mol⁻¹ respectively (Fig. 10). The ratio was lowest in the Crooked and Poerua (part of the Crooked sub-catchment), which together make up 61% of the land area in the Brunner catchment and supply 53% of the river flow into the lake. The TN/TP ratio decreased further in the Poerua-Crooked with increasing flow rates (Fig. 10), as a result of increasing TP concentrations (Rutherford et al. 2008). The TN/TP ratio was highest in the catchment of the Orangipuku (TN/TP = 66 mol mol⁻¹) which drains only 14% of the catchment but is the most intensively developed catchment (Rutherford et al. 2008).

In the Orangipuku TN concentrations were highest (mean 402 TN mg m⁻³, compared with a mean 85 to 268 TN mg m⁻³ for the other rivers). However, its TP load was relative modest (mean 12 mg TP m⁻³, compared with mean 3 to 35 mg TP m⁻³ for the other rivers), resulting in high TN/TP ratios. TP concentrations were lowest in the Carew and Hohonu rivers which drain the least developed catchments (mean 4 mg TP m⁻³), six fold less than in the more developed Poerua-Crooked catchment (Rutherford et al. 2008). TN/TP ratios in the Carew and Hohonu rivers were intermediate (58 and 57 mol mol⁻¹). In the three rivers of the more developed catchments DIN was a larger % of TN (27, 54 and 80% respectively in the Poerua, Crooked, and Orangipuku, flow weighted) compared with the Carew and Hohonu rivers (13 and 22% respectively). In the Carew and Hohonu rivers a larger % of TN (84 and 67% respectively) was accounted for by DON than in the Poerua, Crooked, and Orangipuku (18, 31 and 15% respectively; see also Fig. 4 in Rutherford et al. 2008). In the lake DON was 35% of TN.

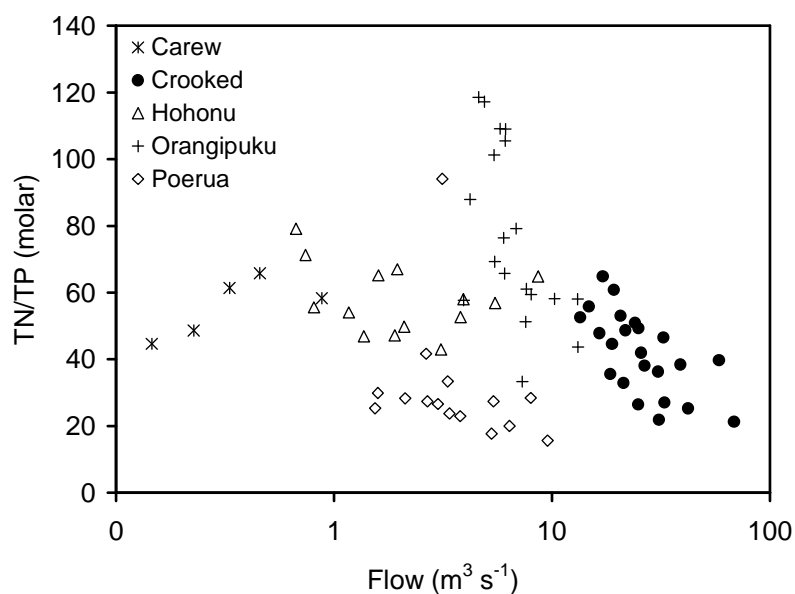


Figure 10: Nutrient ratios in the main tributaries draining to Lake Brunner.

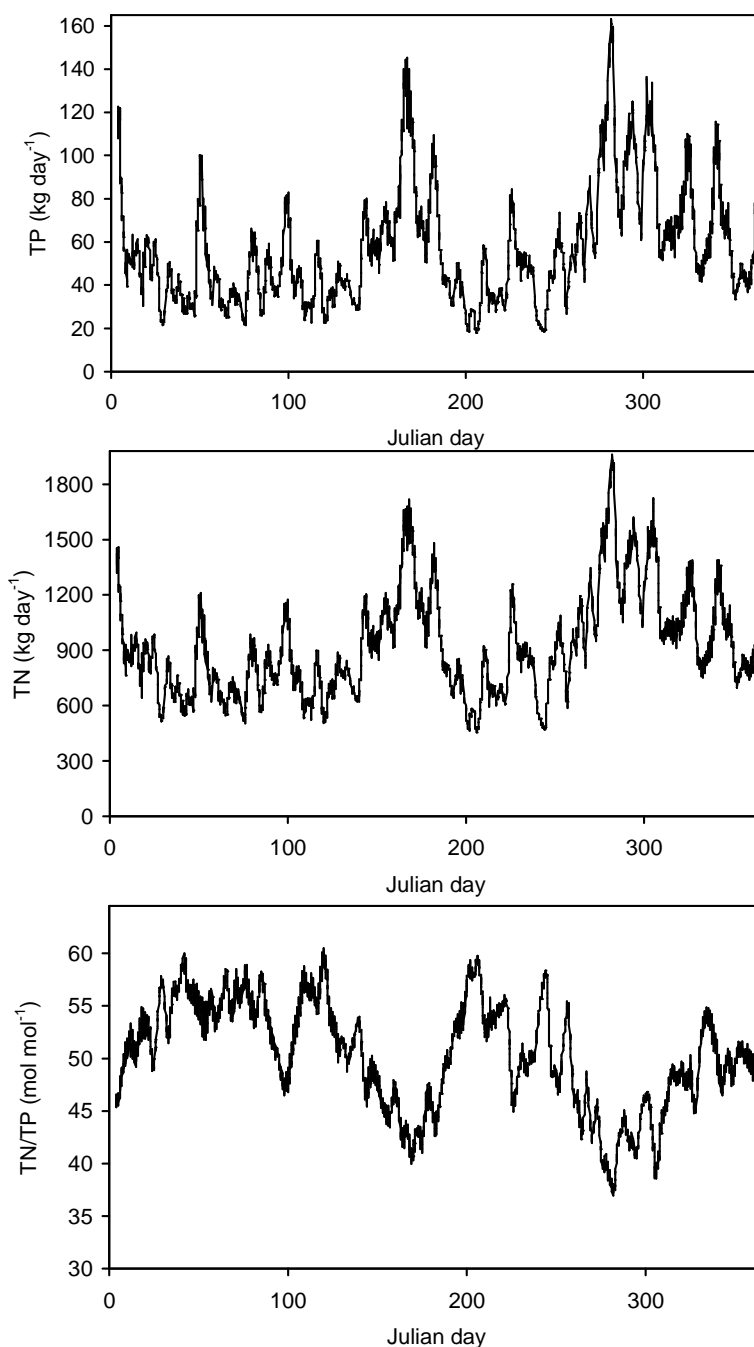


Figure 11: Thirty-day moving averages of total nutrient loading by the tributaries, sorted for day of the year. Loads in the gauged Crooked-Poerua, Hohonu and Orangipuku rivers, which make up 74% of the tributary flow into Lake Brunner, were calculated using flow dependent relationships prepared by Rutherford et al. (2008). In the remaining ungauged tributaries (26% of total inflow) the concentrations of TP and TN were assumed to be similar to the means in the forested catchment of the Carew River (3.5 and 85.5 mg m⁻³ respectively) and flow independent. Daily flow rates were taken from Rutherford et al. (2008).

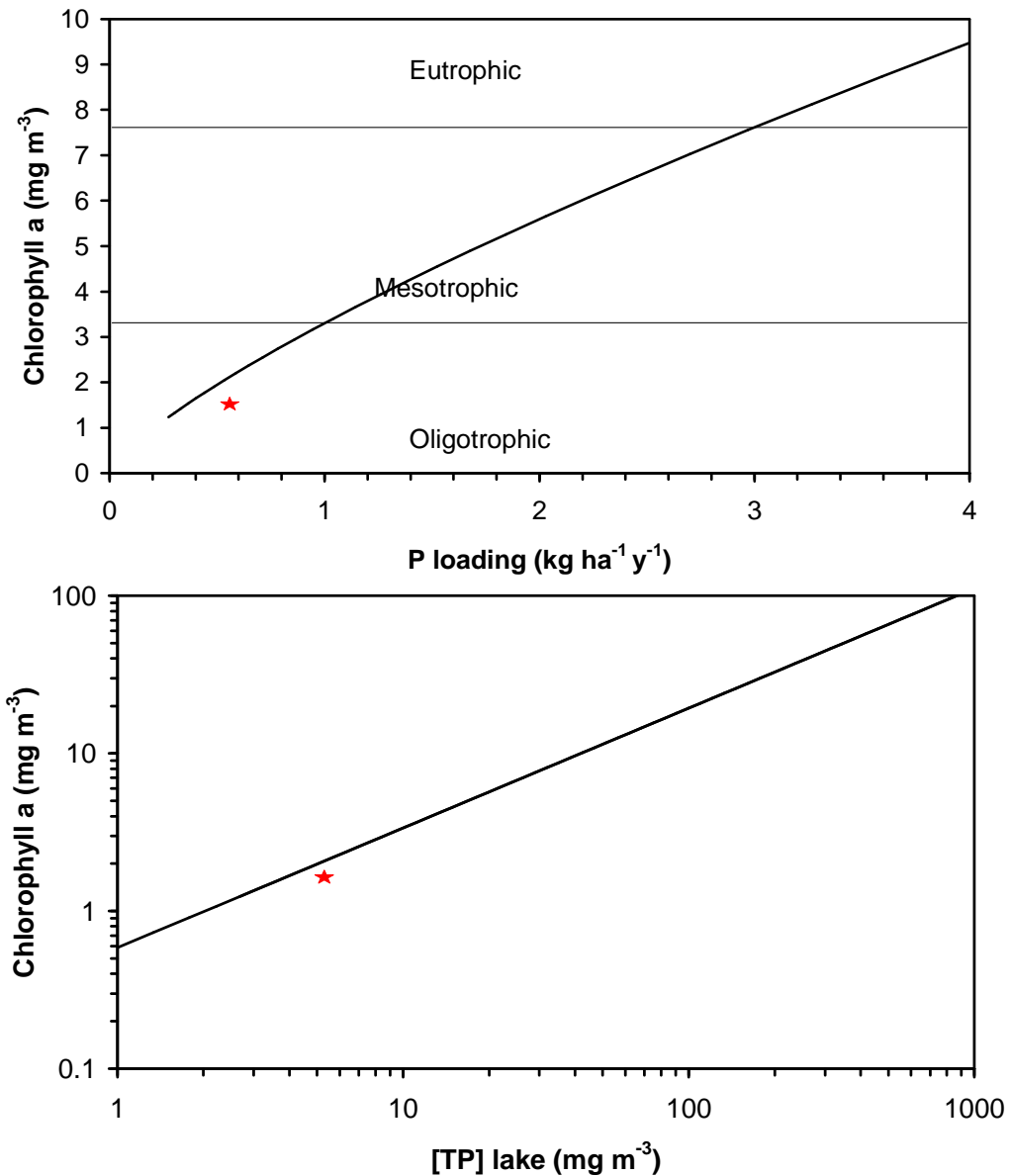


Figure 12: The predicted relation between annual average chlorophyll *a* concentrations and P loading rates (kg per hectare land area per year, upper panel) and TP concentration in the lake (lower panel), as derived from an empirical relation between concentrations of annual average chlorophyll *a* and total phosphorus in various lakes. The relationship is from Wetzel (2001) which improved earlier relationships derived by Dillon and Rigler (1974), Oglesby and Schaffner (1978) and others. Trophic states are indicated by horizontal lines, as suggested by critical levels of lake P concentrations. The present situation is indicated by the red star.

Nutrient loading by inflowing rivers is highest in June and October-November, at which time the TN/TP ratio is lowest (Fig. 11). The seasonal patterns in nutrient loading and in inflow TN/TP ratios are not reflected by nutrient concentrations and TN/TP trends in the lake (Figs. 5 & 6).

2.10 Predicted algal biomass proxies

Based on predicted TP concentrations in the lake, Lake Brunner is predicted to become mesotrophic when annual average chlorophyll *a* concentrations exceed about 3 mg m^{-3} and eutrophic when chlorophyll *a* concentrations exceed 7.5 mg m^{-3} (Fig. 12). The present situation (indicated by the red star in Fig. 12), is slightly below the predicted curve. In lakes where the TN/TP ratio is high, in other words where phosphorus is limiting like in Lake Brunner, the relation between TP and chlorophyll *a* is expected to be close to the fitted curve.

The ranges of chlorophyll *a*, TP and Secchi depths found in Lake Brunner are too small to derive adequate relationships that can be used for extrapolation to predict Secchi depth at higher TP levels than found so far. For instance, linear relations between chlorophyll *a* and Secchi depth, and between TP and Secchi depth, derived from the available data predict zero transparency at P loading rates of about $2.5 \text{ kg ha}^{-1} \text{ y}^{-1}$, in other words below levels at which the lake is expected to become eutrophic (Figs. 8 & 12). Relationships from literature based on larger ranges of Secchi depth and chlorophyll *a* may be used to predict transparency at high P loading rates.

Such a relation of Secchi disk transparency with P loading rates can be derived from a relation with chlorophyll *a* concentration, given by Oglesby and Schaffner (1978; Fig.13). The relation agrees for the estimated P loading and the present transparency in Lake Brunner. The relation is expected to hold especially well at low end of the range of TP concentrations for which the relation was derived (7 to 40 mg m^{-3} TP). However, the relation overestimates Secchi disk transparency in Lake Brunner from the chlorophyll *a* concentration, by about 2 m. The discrepancy may be explained by non-algal turbidity (Lind 1986) and by dissolved colour, which is expected to be high in Westland beech forest lakes stained by dissolved organic carbon (DOC), although Lake Brunner is less stained than other beech forest lakes (Paerl et al. 1979). Turbidity was measured in Lake Brunner only since 2003 (personal communication J. Horrox) and was on average 5.3 NTU. The correlation of turbidity with Secchi disk depth ($R^2 = 0.29$) was similar to the correlation between chlorophyll *a* concentration and Secchi disk depth in the same period ($R^2 = 0.34$). An effect of non-algal turbidity on

transparency may explain why while nutrient concentrations suggest an oligotrophic status for the lake, the Secchi disk depth suggests a state closer to that of a mesotrophic system (section 2.1).

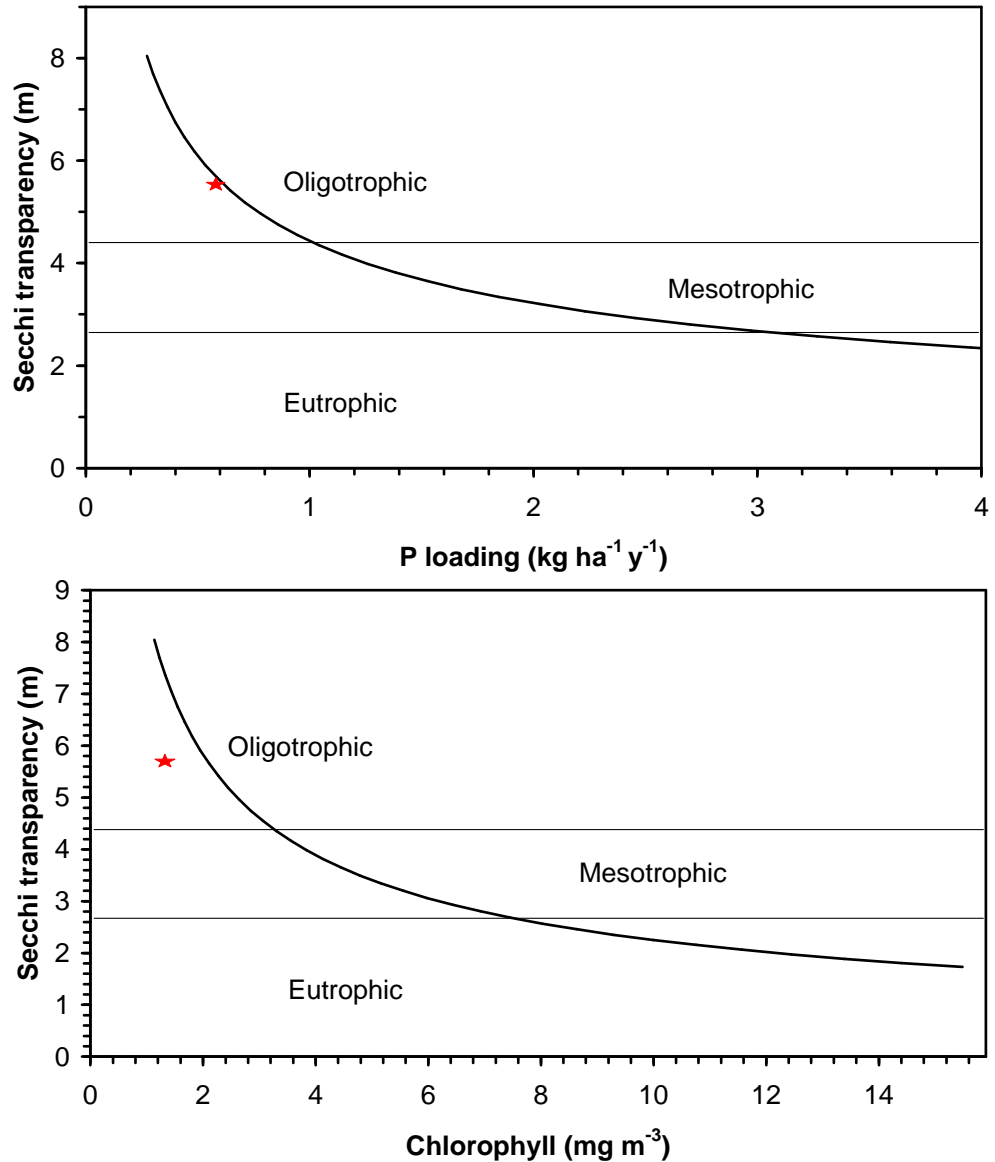


Figure 13: Predicted relationship between phosphorus loading (kg per hectare land area per year), chlorophyll *a* (from Fig. 12) and Secchi disk transparency, as estimated by Oglesby and Schaffner (1978) from chlorophyll *a* concentrations in the lake. Lines separating trophic status are based on the relation with total phosphorus concentrations in the lake (Fig. 8) and the red star is at the position of the estimated phosphorus loading (upper panel), the 1992-2008 mean chlorophyll *a* concentration (lower panel) and the 1992-2008 mean Secchi depth.

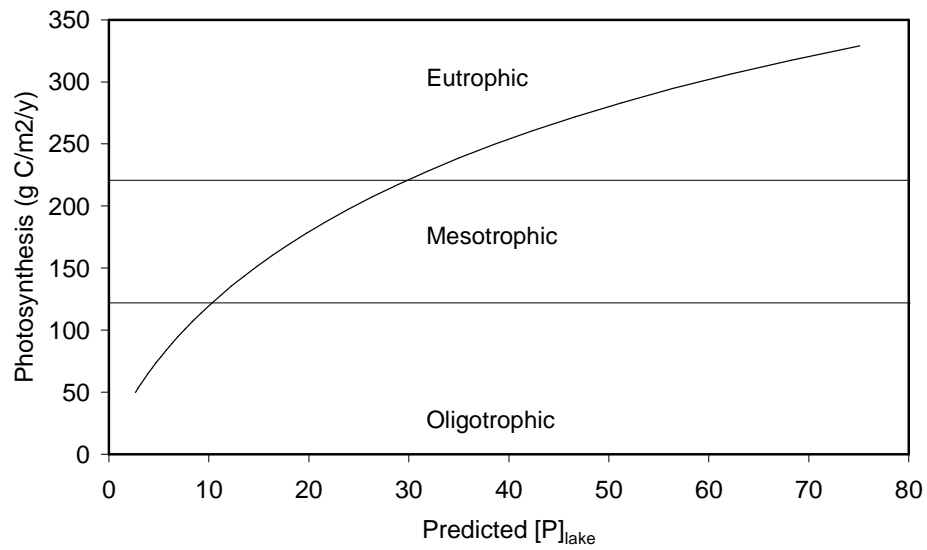


Figure 14: Predicted relationship between total phosphorus concentrations in the lake and rates of primary production, based on a relation with phosphorus loading and residence time given by Wetzel (2001, pg 281).

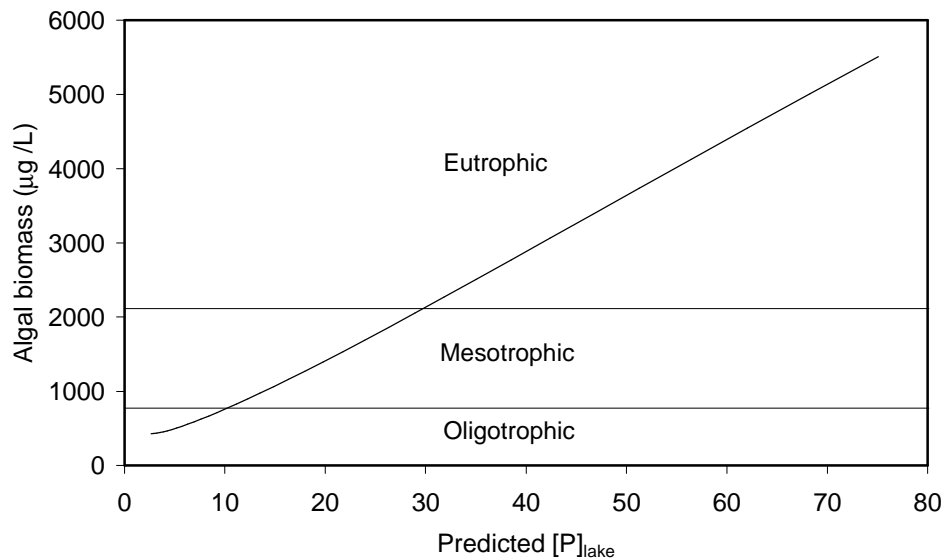


Figure 15: Predicted relationship between total phosphorus concentrations in the lake and algal biomass (wet weight), based on a third order polynomial of log transformed data (reported by Watson et al. 1992).

The relation between rates of primary productivity as predicted from phosphorus loading rates (Fig. 14) is non-linear, as a result of self-shading by high algal biomass (Fig. 15) at high levels of productivity (Wetzel 2001). Present primary productivity is estimated to be about $85 \text{ g C m}^{-2} \text{ y}^{-1}$, which follows from present loading rates (Fig. 14; Table 3). Chlorophyll *a* concentrations also respond non-linearly to increased phosphorus levels (as seen in Fig. 12). In addition, the relation of algal biomass with phosphorus levels is non-linear, sigmoidal, which becomes apparent at concentrations higher than examined here (Fig. 15). The equations used for the relationships in Figures 12 to 15 are given in Table 3. As suggested by Oglesby and Schaffner (1978), these regressions may be used in the development of management strategies for lakes.

Table 3: Relationships between concentrations of phosphorus and epilimnetic chlorophyll *a* in the lake, hydraulic residence time, Secchi depth, primary productivity and algal biomass used in the preparation of Figs. 12-15. See figures for units.

Equation	Dependent Y	Independent X
$Y = 0.55\{X / (1 + \sqrt{T_w})\}^{0.76}$	Chlorophyll <i>a</i> concentration	Total phosphorus concentration (lake)
$\text{Log } Y = 0.961 - 0.606 \text{ Log } X$	Secchi disk depth	Chlorophyll <i>a</i> concentration
$Y = 6.985 \frac{X^{0.76}}{0.29 + 0.011X^{0.76}}$	Primary production	$[\text{TP}]_{\text{inflow}} / (1 + \sqrt{T_w})$
$Y = 2.82 - 0.92X + 1.24X^2 - 0.26X^3$	Log total algal biomass	Log total phosphorus concentration (lake)

Oxygen consumption in the hypolimnion is crucial for the relations between nutrient loading, epilimnetic nutrient and chlorophyll *a* concentrations, Secchi depth, algal biomass (Fig. 15) and rates of primary productivity (Fig. 14). At present the hypolimnion in the centre of the lake is well oxygenated. The most important change in a lake ecosystem occurs when rates of oxygen consumption, driven by increased nutrient loading, excess production, sedimentation of organic matter and subsequent decomposition in deeper water, exceed the production of oxygen and the transport rates of oxygen to bottom water. Bottom water anoxia can drive release of phosphorus from sediments and would provide a positive feedback further enhancing algal

blooms. An important question is to what extent the productivity in the lake can be allowed to be enhanced by increasing P loading rates, before the bottom water becomes anoxic.

It would be feasible to estimate how much organic carbon would suffice to consume all oxygen present in the hypolimnion during the stratified period, i.e., when it can be assumed that little oxygen arrives from the surface layer where it is in contact and exchanges with the atmosphere. However, the proportions of imported organic carbon (not measured at Lake Brunner but can be extrapolated from data elsewhere) versus in-lake production of organic carbon by phytoplankton should be taken into account (and other sources and sinks of fixed carbon such as the loss of organic carbon by permanent burial in the sediment, and oxygen consumption by nitrification). Second, a relation between P loading and rates of net photosynthesis must be confirmed. Such a relationship will depend on seasonal factors such as temperature and light availability and other factors such as dominant plankton species, zooplankton grazing rates and recycling rates within the epilimnion. Relations between measures of algal biomass such as chlorophyll *a* and Secchi depth and rates of productivity are not always straightforward because rates of turnover of biomass may vary and because of variability in transparency driven by non-algal sources (Lind 1986). In addition to algal biomass, allochthonous matter, resuspended bottom sediments and humic substances can affect transparency while limiting light availability for primary production.

Linking predicted oxygen consumption and internal P loading by release from the sediment directly with external P loading is complex and requires observations of phosphorus retention when partial anoxia develops, or of phosphorus release rates from the sediment (Nurnberg 1984).

The fact that most of the primary production in Lake Brunner occurs during the stratified period may make it more vulnerable to drivers of anoxia in the hypolimnion. Oxygen concentrations in the hypolimnion were consistently drawn down in each warm stratified season between 1992 and 1995 (Burns and Rutherford 1998), although the oxygen concentration never fell below about 7 g m^{-3} (about 60% saturation; the lowest value was usually reached in May or June). Throughout each stratified season the decrease in oxygen concentration over time was linear ($R > 0.94$; at the same sampling site where data were collected for this report), suggesting a constant rate of oxygen consumption of $9.0 \text{ mg m}^{-3} \text{ day}^{-1}$ (with a slow rate of reoxygenation by diffusion taken into account). In order to inform and assist the management of Lake

Brunner, it is recommended that hypolimnetic oxygen consumption is monitored regularly during stratified seasons, in combination with the estimation of annual P retention, from P loading rates and its concentration in the lake. In addition, regional long term oscillations in rainfall, linked to cyclical climate controls, can result in cycles with timescales in the order of decades in runoff and export of DOC and nutrients from the catchment to the lake. Such long term cycles in rainfall can result in long term cycles in transparency and productivity in the lake (Gaiser et al. 2009). It is therefore recommended to examine historical records of interannual variability in rainfall in the catchment and its effect on Lake Brunner's water quality.

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