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**Assessment of effects of increased  
nutrient concentrations in streams and  
lakes of the Upper Waitaki Basin due  
to catchment land use changes**

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NIWA Client Report: CHC2005-003  
February 2005

NIWA Project: GPF05501

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**Assessment of effects of increased nutrient concentrations in streams and lakes of the Upper Waitaki Basin due to catchment land use changes**

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# Contents

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Executive Summary	i
1. Introduction	1
2. Rivers	2
2.1. Method	2
2.2. Results	4
2.3. Discussion	5
2.4. Conclusion	6
3. Lakes	6
3.1. Methods	6
3.2. Results	4
3.3. Discussion	5
3.4. Conclusion	9
4. References	10

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## Executive Summary -- **DRAFT**

This work examines the effect of increased nutrient concentrations on streams and lakes in the Upper Waitaki Basin resulting from potential changes in agricultural land use and management practices (irrigation). Streams and lakes may be nutrient enriched due to non-point sources resulting from agricultural land use, particularly when irrigation runoff and discharge to groundwater occurs. The main objective of this work is to assess whether potential future land use and management changes could lead to adverse effects on streams and lakes, specifically by producing nuisance growths of periphyton, phytoplankton and/or macrophytes.

This report builds on the outputs from several earlier reports that have been produced by others specifically for this purpose. In brief the earlier reports are as follows:

- i) Project Waitaki Irrigation Investigations (Glasson Potts Fowler, 2004). This report assessed existing irrigation and land use in the Waitaki basin and investigated the feasibility of irrigation for a number of possible future land uses. The report defined areas on GIS maps depicting existing land use and three potential future land use intensification scenarios.
- ii) Groundwater in the Upper Waitaki catchment (White et al., 2004). This report assessed irrigation impacts on nitrogen in groundwater, and modelled annual loads of nitrogen from 11 zones within the catchment for the existing land use and three potential land use intensification scenarios.
- iii) Estimation of phosphorus loads from zones within the Upper Waitaki Basin (McDowell, 2004). This report assessed irrigation impacts on phosphorus loads from 11 zones within the catchment for the existing land use and three potential land use intensification scenarios.

We have used the outputs from these three reports in two separate analyses, one for rivers and one for lakes. The area of study is large, being the whole of the Upper Waitaki Basin, and the analysis is based on a relatively small amount of existing data. We have therefore conducted the analyses at a relatively broad scale. This means general predictions are made for whole lakes and rivers, rather than for parts of lakes or sections of rivers. The methods and results are presented in this report, together with a discussion of the assumptions and the rationale for the analytical approach used. We have tested the sensitivity of some of the assumptions and where possible we have used existing data, literature and/or practical observations to justify the methods and assumptions. The choice of methods and assumptions has also been based on expert judgement. The key conclusions are summarised below and these should be considered within the context of the broad nature of the assessment and the many assumptions described in the body of the report.

### *Predicted effects on rivers*

The assessment indicates that the land use development scenarios could produce a minimum twofold increase in algae biomass in the Twizel River (Scenario 1) and would increase biomass in this River sufficiently to exceed national (MfE 2000) periphyton guidelines even under the least intensive land use scenario. For other streams of the Waitaki Basin, the assessment indicates that the severity and frequency of exceedence of algae biomass guidelines would increase by a factor of between 1.5 to more than 3 depending on the land use scenario. Proliferations of periphyton would greatly change the character and may potentially decrease the value of these waterways.

Our assessment, therefore, is that land use changes are likely to change algae biomass and trophic state in streams of the Upper Waitaki Basin and cause breaches in the national periphyton guidelines. Given the currently very high quality of habitat in these systems, the acceptability of these changes should be judged based on the objectives for managing these streams.

### *Predicted effects on lakes*

For lakes Benmore (North and West arm), Aviemore and Waitaki, our model predicts that, based on the nutrient loading forecasts, phytoplankton growth, as determined by chlorophyll *a*, will reach eutrophic and mesotrophic status for Scenarios 1 and 2, respectively. Increases in nutrient inputs to the primary producers in these lakes may result in:

- Formation of algal blooms, resulting in discolouration of the water during period of peak growth (mid summer).
- Shift in dominant species (for phytoplankton, periphyton and macrophytes) to weedy, or undesirable species.
- Displacement of sensitive species resulting in loss of biodiversity.
- Vegetation decline due to smothering of by algae.
- Loss of aesthetic values and impeded recreational activities.
- Economic loss through impediment of hydro-electrical generation from excessive macrophyte or periphyton growth blocking intacts.

Due to other controlling factors, such as light availability, substrate suitability, wave exposure and water level fluctuations, the proposed nutrient loading rates are unlikely to impact on the growth of phytoplankton, macrophytes and periphyton in lakes Tekapo, Pukaki and Ohau.

## 1. Introduction

This work examines the effect of increased nutrient concentrations on streams and lakes in the Upper Waitaki Basin resulting from potential changes in agricultural land use and management practices (irrigation). Streams and lakes may be nutrient enriched due to non-point sources resulting from agricultural land use, particularly when irrigation runoff and discharge to groundwater occurs. The main objective of this work is to assess whether potential future land use and management changes could lead to adverse effects on streams and lakes, specifically by producing nuisance growths of periphyton, phytoplankton and/or macrophytes.

Some increase in nutrients may be acceptable and result in little change to the stream or lake ecosystem or its valued resources. However, excess nutrients may adversely affect values by promoting high algal biomass. In streams, excessive algal growth can smother habitat and may also adversely affect fish and invertebrates due to fluctuations in dissolved oxygen and pH levels caused by plant respiration. Excessive algal cover in streams also has social and human use affects such as reducing recreational and aesthetic quality (Biggs 2000; MFE 2000). In lakes, excessive growth of aquatic plants (macrophytes) may smother lake edge habitat or cause floating rafts of weed that adversely affect recreation values and lead to management problems for water users (e.g., irrigators and hydropower generators). Also in lakes, excessive phytoplankton growth or algal “blooms” may change the colour of the lake water or lead to toxicity problems for fish or recreational users, as well as potentially causing the same dissolved oxygen and pH fluctuation problems mentioned for streams. Management of stream and lake nutrient concentrations is, therefore, a broad-scale management issue.

The following report sets out the methods used to assess the changes to algae biomass in the streams and lakes of Upper Waitaki Basin that are due to increased nutrient loads under different future land use scenarios. . This report builds on the outputs from several earlier reports that have been produced by others specifically for this purpose. In brief the earlier reports have been as follows:

- iv) Project Waitaki Irrigation Investigations (Glasson Potts Fowler, 2004). This report assessed existing irrigation and land use in the Waitaki basin and investigated the feasibility of irrigation for a number of possible future land uses. From this report Glasson Potts Fowler defined areas on GIS maps depicting existing land use and three potential future land use intensification scenarios.

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- v) Groundwater in the Upper Waitaki catchment (White et al. 2004). This report assessed irrigation impacts on nitrogen in groundwater, and modelled annual loads of nitrogen from 11 zones within the catchment for the existing land use and three potential land use intensification scenarios.
- vi) Estimation of phosphorus loads from zones within the Upper Waitaki basin McDowell (2004). This report assessed irrigation impacts on phosphorus loads from 11 zones within the catchment for the existing land use and three potential land use intensification scenarios.

The outputs from these reports have been used in two separate analyses, one for rivers and one for lakes as described below.

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## 2. Rivers

### 2.1. Method

There is little available stream nutrient data for streams in the Upper Waitaki Basin. A set of data for a single sampling occasion was available from Environment Canterbury (ECan). A single sampling occasion provides an indication of relative differences in nutrient status among streams. However, a single sampling occasion cannot be used to assess the effect of nutrients on algae biomass because this is determined by the long-term average nutrient status of a stream. Annual loads of nitrogen and phosphorus have been modelled for the existing land use and three potential land use intensification scenarios by White et al. (2004) and McDowell (2004) respectively. The modelled nutrient run-off loads were converted to in-stream concentrations and the ECan data was used as a check on the assessment.

The assessment was based on estimates of nitrogen, phosphorus, mean stream flow and stream flood frequency at nine locations: Tekapo at Grays Hill, Twizel at Lk Poaka, Twizel at SHBr, Mary Burn (upper) at Mt MacDonald, Mary Burn (lower) at Maryhill, Irishman at Windy Ridge, Forks at Balmoral, Omarama Above Tara Hills and Wairepo Creek (Table 1). Predictions of annual fluxes of nitrogen and flow due to irrigation water runoff were derived from the SPASMO model (White et al. 2004).

18/04/05

**Table 1: Data used for the assessment. FRE3 and mean flow have been established from flow data for those assessment locations with a flow site number. Actual DIN and DRP concentrations measured by Environment Canterbury are shown. All other DIN and DRP concentrations are those based on annual loads estimated by White et al. (2004), and McDowell (2004) respectively.**

Assessment location River Site name	Flow Site No	FRE3	Mean Flow (l/s)	DIN (ECan) (mg/m <sup>3</sup> )	DRP (ECan) (mg/m <sup>3</sup> )	Assumed catchment	Existing		Scenario1		Scenario 2		Scenario 3		
							DIN (mg/m <sup>3</sup> )	DRP (mg/m <sup>3</sup> )	DIN (mg/m <sup>3</sup> )	DRP (mg/m <sup>3</sup> )	DIN (mg/m <sup>3</sup> )	DRP (mg/m <sup>3</sup> )	DIN (mg/m <sup>3</sup> )	DRP (mg/m <sup>3</sup> )	
Tekapo	GraysHill	5.42	7809	55	5	Sum Zone2	1302.6	1.5	5641.8	18.1	2852.6	7.4	1382.6	1.5	
Twizel	Lk Poaka	71117	12.23	2573	33	0.5x0.5xZone4	599.3	0.7	2809.4	8.4	1662.7	4.6	1397.0	3.3	
Twizel	SHBr	71121	8.85	4638	33	0.5x0.5xZone4	340.8	0.4	1628.6	4.9	953.0	2.7	800.7	1.9	
Mary Burn (upper)	Mt MacDonald	71122	6.17	566	26	0.5x0.33x0.5xZone2	1461.8	1.7	6266.8	20.1	3188.2	8.2	1551.6	1.7	
Mary Burn (lower)	Maryhill	71127	2.36	689	55	0.33x0.5xZone2	2235.0	2.9	9130.4	32.3	4780.5	13.6	2372.3	2.9	
Irishman	Windy Ridge	71128	7.28	1348	23	0.33x0.5xZone2	1250.8	1.6	5435.6	19.2	2742.8	7.8	1327.7	1.6	
Forks	Balmoral	71129	5.87	3202	24	0.33x0.5xZone2	558.7	0.7	2541.8	9.0	1247.2	3.5	593.0	0.7	
Omarama	Above Tara Hills	71189	4.53	1535	n.a.	n.a.	0.5x0.3xZone7	451.3	0.5	1941.9	6.7	795.7	2.1	580.6	1.1
Wairepo Creek			1.80	1075	120	9	0.5xZone6	1140.8	1.4	4410.5	15.5	1793.4	2.7	1321.5	4.0

Predictions of annual fluxes of phosphorus were modelled by McDowell (2004). Mean flows for streams in the Upper Waitaki Basin were derived from measured data where available and estimates made from NIWA models where flows not available (Norton, pers comm.). Stream flood frequency was measured using FRE3 (the mean number of flood events per year that exceed three times the median flow). FRE3 was estimated from continuous flow records, where these were available, and estimates based on adjacent sites with similar catchment characteristics for the two streams that did not have flow recorders (Tekapo at Grays Hill and Wairepo Creek) (Ned Norton pers com.)

Estimates of all parameters were made for four modelled scenarios that included existing land use and three levels of agricultural intensification (White et al. 2004). The modelled annual nitrogen and phosphorus loads were converted to mean concentrations of dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DRP) by dividing the annual mass of each nutrient by the estimated mean stream flow (Table 1). Concentration estimates were based on an estimate of the proportion of each of several land use zones that comprises the catchment area of the stream at each assessment location (Paul White pers comm.) (see Table 1).

Yearly maximum algae biomass in the stream at each assessment location was estimated using the model of Biggs' (2000). This model assumes that algae biomass in gravel bed streams is a function of the counteracting processes of resource supply (causing algal growth) and biomass loss. Growth rate is determined primarily by nutrient supply and light, and biomass loss is determined by hydrological disturbance (i.e., velocity increase and substrate instability due to flood flows) and invertebrate grazing. The model accounts for over 70% of the variability in maximum algal biomass using mean monthly DIN and DRP and 'days of accrual', which is the time between flood events that significantly increases velocity and removes algae.

The New Zealand periphyton guideline (MFE 2000) uses Biggs' (2000) model to define nutrient concentration criteria for rivers based on yearly maximum algae biomass. In this assessment, however, the equations have been used to assess the biomass that could arise from the existing and proposed land use scenarios, based on the nutrient concentrations. Yearly maximum benthic algae biomass is measured by the chlorophyll *a* concentration ( $\text{mg m}^{-2}$ ).

Equations (1) and (2) provide a prediction of yearly maximum benthic algae biomass.

$$\text{Log}_{10}(\text{maximum chl. } a) = 4.285(\text{log}_{10} \text{ Da}) - 0.929(\text{log}_{10} \text{ Da})^2 + (0.504 \text{ Log}_{10} \text{ DIN}) - 2.946 \quad (1)$$

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$$\text{Log}_{10}(\text{maximum chl. } a) = 4.716 (\text{log}_{10} \text{Da}) - 1.076 (\text{log}_{10} \text{Da})^2 + (0.494 \text{Log}_{10} \text{DRP}) - 2.741 \quad (2)$$

Yearly maximum algae biomass was estimated using equations 1 and 2 using the modelled nutrient concentrations at each assessment location for each scenario (Table 1). In equation 1 and 2 the days of accrual (Da) is the average time between significant floods and is measured using a flow statistic FRE3. Da is based on the following equation:

$$\text{Da} = \frac{1}{\text{FRE3}} \times 365.25 \quad (3)$$

## 2.2. Results

Yearly maximum biomass was assessed for the four scenarios at nine assessment locations. The estimates of DIN and DRP concentrations are shown in Table 1. In all cases (sites and scenarios) the ratios of DIN to DRP far exceed 30 to 1. Nitrogen to phosphorus ratios of less than thirty can be associated with either nitrogen or phosphorus limitation. However, ratios of greater than 30 are always associated with phosphorus limitation of algae growth (Biggs 2000). Thus, the predicted maximum chlorophyll *a* concentrations (shown in Table 2) are computed from the limiting phosphorous concentration using equation 2. The assessment indicates that algae biomass is highest under both the existing and future land use scenarios in the Mary Burn and Wairepo catchments. This finding is supported by the available water quality data (ECan 2004), which provides some confidence in the various assumptions made in the modelling.

**Table 2: Predicted yearly maximum chlorophyll *a* concentration (mg m<sup>-2</sup>) at assessment sites based on modelled DRP.**

Assessment location					
River	Site name	Existing	Scenario1	Scenario 2	Scenario 3
Tekapo	Grays Hill	237	806	516	237
Twizel	Lk Poaka	62	214	160	135
Twizel	SHBr	73	256	190	161
Mary Burn (upper)	Mt MacDonald	225	761	489	225
Mary Burn (lower)	Maryhill	450	1485	968	450
Irishman	Windy Ridge	186	633	405	186
Forks	Balmoral	153	534	337	153
Omarama	Above Tara Hills	160	557	316	225
Wairepo Ck		306	1000	421	515

### 2.3. Discussion

The New Zealand periphyton guideline (MFE 2000) uses yearly maximum and mean monthly algae biomass to define the guideline conditions for rivers. This assessment has estimated yearly maximum biomass and these can be compared with the guidelines. The guideline suggests the maximum chlorophyll *a* concentration of 50 mg m<sup>-2</sup> and 120 mg m<sup>-2</sup> for filamentous green algae and 200 mg m<sup>-2</sup> for diatoms. These biomasses define the boundaries between oligotrophic and mesotrophic, and mesotrophic and eutrophic states respectively.

The yearly maximum chlorophyll *a* concentration suggested in the New Zealand periphyton guideline (MFE 2000) for a high level of protection for the instream community that should be applied for the protection of “benthic invertebrate biodiversity” is the oligotrophic - mesotrophic boundary (i.e., 50 mg m<sup>-2</sup>). The higher biomass of 120 mg m<sup>-2</sup> (which assumes a ‘worst case’ algae community that is dominated by filamentous green algae) is the suggested guideline for aesthetic and trout habitat and angling. Table 2 indicates that the lower biomass (high level of protection boundary) is exceeded at all assessment locations and under all scenarios. The higher biomass boundary is not exceeded in the Twizel River at the Lk Poaka and SHBr sites under the existing scenario. The low predicted biomass in the Twizel River is attributable to both lower nutrient concentrations and higher flood frequency (Table 1). All other sites are predicted to exceed the higher biomass boundary under the existing landuse, with the predicted yearly maximum biomass at the Mary Burn (lower) at Maryhill and Wairepo Ck sites exceeding this by a factor of more than two. This is a result that can be expected because these streams have relatively low flood frequency (Table 1).

Table 2 indicates that all sites would have their yearly maximum biomass increase by a factor of approximately 3, 2 and 1.5 for scenarios one, two and three respectively. As well as increasing the yearly maximum algae biomass, algae proliferations would become increasingly frequent under scenarios three, two and one respectively. These results should be interpreted as the lower boundary for yearly maximum algae biomass because it has assumed that the annual flux of nutrients is evenly distributed throughout the year. In reality nutrient concentrations are likely to be higher than the annual mean during spring and summer because this is when irrigation occurs. In addition, spring and summer coincide with low stream flows, warm temperatures and long sunlight hours, all of which support algae proliferation. It is considered, therefore, that the assessment is likely to have underestimated the potential maximum algae biomass, particularly for locations where conditions are favourable, such as immediately downstream from irrigation runoff.

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The ECan (2004) report found that “there are no indications of appreciable degradation of water quality in areas of the MacKenzie basin monitored so far”. The report did find indications of nutrient enrichment in the Mary Burn and Wairepo catchments. Our assessment supports this finding and suggests that streams in these two catchments, in particular, will be most affected by land use change under any scenario (including the existing case). Our assessment suggests that the existing yearly maximum biomass could exceed the higher NZ guideline value of 120 mg m<sup>-2</sup>. However, the ECan report indicates that enrichment in the Mary Burn is “not currently showing any observable effect”. The reasons that algae proliferations have not become an issue so far may be because invertebrate grazing is currently able to control growth. However, the report suggests “it may take very little in the way of further nutrient inputs to upset the ecological balance” and that enrichment “may lead to loss of biodiversity as sensitive taxa respond to increased conductivity/enrichment”. Our analysis supports this conclusion.

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#### 2.4. Conclusion

The assessment indicates that the land use development scenarios could produce a minimum twofold increase in algae biomass in the Twizel River (Scenario 1) and would increase biomass in the River sufficiently to exceed the national guidelines even under the least intensive land use scenario (Scenario 1). For other streams of the Waitaki Basin, the assessment indicates that the severity and frequency of exceedence of algae biomass guidelines would increase by a factor of between 1.5 to more than 3 depending on the land use scenario. Proliferations of periphyton would greatly change the character and may potentially decrease the value of these waterways.

Our assessment, therefore, is that land use changes are likely to change algae biomass and trophic state in streams of the Upper Waitaki Basin and cause breaches in the MfE periphyton guidelines. Given the currently very high quality of habitat in these systems, the acceptability of these changes should be judged based on the objectives for managing these streams.

### 3. Lakes

#### 3.1. Methods

This section describes methods used to predict long-term in-lake concentrations of nutrients and algal biomass (as chlorophyll *a* concentrations), based on nitrogen and phosphorus loads supplied by White et al. (2004) and McDowell (2004), respectively, combined with simple empirical models that relate total nitrogen and total phosphorus

to chlorophyll *a* (Chl *a*) concentration. Methods pertaining to data obtained during field sampling and subsequent bioassays are described in Appendix A.

As for streams, there is little available nutrient data for lakes in the Upper Waitaki Basin. Data from two sampling occasions were available from Environment Canterbury (Ecan 2004) for lakes Benmore and Ruataniwha. Data on Chl *a* concentrations were also obtained during one sampling (26 Aug 2004) in lakes Pukaki, Ohau, Ruataniwha and the West and North Arms of Lake Benmore, carried out by NIWA as part of the present study. These data are summarised in Table 3, together with data obtained during surveys carried out on Lake Tekapo from March – November 1992 (unpublished NIWA data).

The very limited nutrient and chlorophyll data available give an indication of the present oligotrophic conditions of the lakes. They were used to estimate baseline concentrations for total nitrogen (TN) and total phosphorus (TP) in the lakes, to which were added concentrations resulting from the loadings specified in the three irrigation scenarios. The existing Chl *a* data were used as a check against modelled Chl *a* concentrations under the dry land scenario.

The modelling involves two separate steps. The first is the conversion of the TN and TP loads specified by White et al. (2004) and McDowell (2004) into expected in-lake average annual TN and TP concentrations. The second involves the use of the in-lake TN and TP concentrations to estimate likely average annual Chl *a* concentrations.

The method of Dillon and Rigler (1975) was used to predict in-lake concentrations of nutrients based on nutrient concentration in the inflows to the lake and the retention coefficient for the nutrient (see also Ryding and Rast 1989 and Baker et al. 1985 for examples of applications of the method). The retention coefficient is the fraction of the nutrient input that is retained within the lake, usually on a long term, average annual basis,  $R = 1 - M_{out}/M_{in}$ , where  $M_{out}$  = mass of nutrient that leaves the lake, and  $M_{in}$  = mass input to the lake.  $R$  is associated with uptake of nutrient within the lake and subsequent loss to lake sediments due to mortality and sinking. Dillon and Rigler (1975) use a simple mass balance to show that  $M_{in}$ ,  $R$  and total annual water inflow  $Q_{in}$  are related to the in-lake concentration  $c$  by:

$$c = (M_{in} / Q_{in}) \times (1 - R) \quad (4)$$

In principle,  $R$  can be measured directly if all inflows, outflows and mass fluxes entering and leaving a lake are measured. In practice this is rarely possible, and Dillon and Rigler (1975) recommend the use of the following empirical correlation (due to

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Kirchner and Dillon 1975) of  $R$  with the annual areal hydraulic loading,  $q_s = Q_{in} / A_s$ , where  $A_s$  is lake surface area and  $q_s$  has units of m year :

$$R = 0.426 \exp(-0.271q_s) + 0.574 \exp(-0.00949)q_s \quad (5)$$

Nürnberg (1984) has reviewed several alternative formulae for  $R$ . We have repeated our calculations for Nürnberg's (1984) recommended formula, but our results and conclusions are not sensitive to the choice of formula. We have used Equation 5 to estimate  $R$  for all of the lakes. Values of  $R$  and  $Q_{in}$  are given in Table 5.

In the present study, we do not have information on the total load of nutrients from the entire catchment of each lake; we only have load estimates for the land-use subregions shown in the map of White's (2004) Figure 2. Hence we have used Equation 4 to calculate increments to existing lake concentrations as:

$$\Delta c_i = (\Delta M_{in,i} / Q_{in}) \times (1 - R) \quad (5)$$

where  $\Delta c_i$  is the concentration increment due to the mass load from sub-region  $i$ ,  $\Delta M_{in,i}$ . If the lake being considered receives flow from upstream lakes, then similar terms need to be calculated for the lakes that contribute directly to the lake under consideration. Then the final in-lake concentration is then:

$$c_i = c_{baseline} + \Sigma \Delta c_i = c_{baseline} + [\Sigma (\Delta M_{in,i}) / Q_{in}] \times (1 - R) \quad (6)$$

where the summation is over all the sub-regions and upstream lakes that contribute directly to the lake in question, and  $c_{baseline}$  is the baseline nutrient concentration in the lake under present conditions. We assigned baseline concentrations of  $4 \mu\text{g L}^{-1}$  for TP and  $40 \mu\text{g L}^{-1}$  for TN, based on available measured data as summarised in Table 3.

Values for nutrient loads  $\Delta M_{in,i}$  for individual land-use regions given by White et al. (2004) and McDowell (2004) are summarised in Table 4. Total mean annual inflows for each lake, as supplied by Meridian Energy, are given in Table 5. For the purposes of calculating nutrient fluxes leaving the lakes (as in-lake concentration multiplied by the outflow discharge) we assumed inflows and outflows were approximately equal.

Calculations proceeded by following the input pathways for the nutrient flows given in Figure 1, based on White's (2004) Figure 4. Figure 1 differs from White et al.'s (2004) Figure 4 in that we have treated the Northern and Western arms of Lake Benmore as separate basins because of the lack of mixing and circulation between them.

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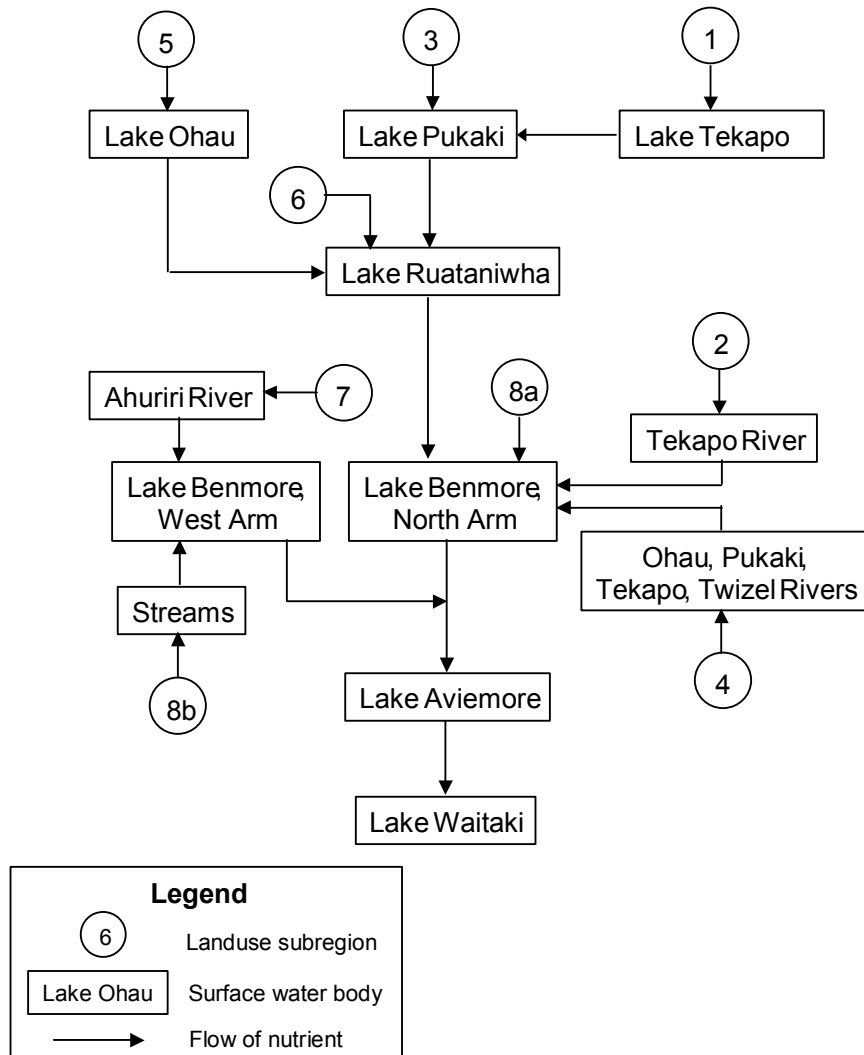


Figure 1: Flow of nutrients from landuse subregions through the Waitaki lakes; redrawn from White (2004) to indicate separation of Northern and Western basins of Lake Benmore.

**Table 4: Nutrient loads from land-use sub-regions, from White et al (2004) and McDowell (2004)**

**Total phosphorus loads, tonnes P / year**

**Irrigation**

<b>Scenario</b>	<b>Zone 1</b>	<b>Zone 2</b>	<b>Zone 3</b>	<b>Zone 4</b>	<b>Zone 5</b>	<b>Zone 6</b>	<b>Zone 7</b>	<b>Zone 8a</b>	<b>Zone 8b</b>	<b>Zone 9</b>	<b>Zone 10</b>
Dry Land	0.045	1.26	0.11	0.70	0.044	0.30	0.35	0.14	0.12	0.019	0.0078
1	0.60	12.13	1.09	6.73	0.37	3.10	4.96	1.43	1.12	0.27	0.078
2	0.42	5.02	1.09	3.48	0.32	0.60	1.42	1.28	0.38	0.27	0.078
3	0.13	1.26	0.11	2.78	0.20	0.70	0.88	0.24	0.23	0.048	0.023

**Total nitrogen loads, tonnes N / year**

**Irrigation**

<b>Scenario</b>	<b>Zone 1</b>	<b>Zone 2</b>	<b>Zone 3</b>	<b>Zone 4</b>	<b>Zone 5</b>	<b>Zone 6</b>	<b>Zone 7</b>	<b>Zone 8a</b>	<b>Zone 8b</b>	<b>Zone 9</b>	<b>Zone 10</b>
Dry Land	18	358	11	206	12	81	150	40	34	8	2
1	80	1681	50	1015	56	344	669	180	163	36	12
2	69	757	50	562	55	120	243	158	65	36	12
3	24	309	9	464	34	83	166	45	44	9	4

**Zone Areas, hectares**

<b>Zone 1</b>	<b>Zone 2</b>	<b>Zone 3</b>	<b>Zone 4</b>	<b>Zone 5</b>	<b>Zone 6</b>	<b>Zone 7</b>	<b>Zone 8a</b>	<b>Zone 8b</b>	<b>Zone 9</b>	<b>Zone 10</b>
2234	41834	1334	23204	1463	9991	17698	4756	3848	959	260

**Table 5: Hydrographic parameters for lakes as used in model**

	Surface Area at Maximum Level, km <sup>2</sup>	Mean Inflow / Outflow Q, m <sup>3</sup> /s	Mean Inflow / Outflow Q, m <sup>3</sup> /yr	Inflow / Lake surface area, q <sub>s</sub> , m/year	Volume at Mean Lake Level, V, 10 <sup>6</sup> m <sup>3</sup>	Residence Time t <sub>w</sub> , days	Residence Time t <sub>w</sub> , years	Average lake depth z <sup>bar</sup> , m	Retention coefficient R (fraction N,P retained)
Lake Tekapo	97.5	81.3	2.57E+09	26.3	6834	973	2.66	70.1	0.45
Lake Pukaki	179	207	6.52E+09	36.5	8643	484	1.33	48.4	0.41
Lake Ohau	61.2	81.3	2.57E+09	41.9	4135	589	1.61	67.6	0.39
Lake Ruataniwha	4.9	261	8.24E+09	1681	31.8	1.4	3.87E-03	6.5	<0.01
L Benmore, North Arm	58.8	308	9.71E+09	165	1504	57	0.15	25.6	0.12
L Benmore, West Arm	15.7	32.2	1.02E+09	64.6	210.0	75	0.21	13.3	0.31
Lake Benmore	74.5	340	1.07E+10	144	1714	58	0.16	23.0	0.15
Lake Aviemore	28.8	357	1.13E+10	391	428	14	0.04	14.9	0.01
Lake Waitaki	6.2	371	1.17E+10	1888	34.6	1.1	2.95E-03	5.6	<0.01

Data from Meridian Energy and Lake Chart Series maps; retention coefficient calculated following Dillon and Rigler (1975)

The second step in the modelling involves predicting Chl *a* concentration from in-lake TP and TN concentrations. Use was made of equations given by Burns et al. (2000) in their protocol for monitoring New Zealand lakes that specify relations between in-lake TN, TC, Chl *a* and a Trophic Level Index (TLI), as:

$$TL_C = 2.22 + 2.54 \log(\text{Chl } a) \quad (7)$$

$$TL_N = -3.61 + 3.01 \log(\text{TN}) \quad (8)$$

$$TL_N = 0.218 + 2.92 \log(\text{TP}) \quad (9)$$

$$TL_C = TL_N = TL_P = TLI \quad (10)$$

where all concentrations have units of  $\mu\text{g L}^{-1}$  and logarithms are base 10. Burns et al. (2000) describe the relation between TLI and lake trophic status, and suggest the following boundaries (Table 6) between trophic states using the TLI:

**Table 6: Values of variables that define the boundaries of different trophic levels (from Burns et al. 2000, Table 4.1)**

Lake Type	TLI	Chl <i>a</i> , $\mu\text{g/L}$	TP, $\mu\text{g/L}$	TN, $\mu\text{g/L}$	Secchi depth, m
Ultra-microtrophic	0 - 1	0.13 - 0.33	0.84 - 1.8	16 - 34	33 - 25
Microtrophic	1 - 2	0.33 - 0.82	1.8 - 4.1	34 - 73	25 - 15
Oligotrophic	2 - 3	0.82 - 2.0	4.1 - 9.0	73 - 157	15 - 7.0
Mesotrophic	3 - 4	2.0 - 5.0	9.0 - 20	157 - 337	7.0 - 2.8
Eutrophic	4 - 5	5.0 - 12	20 - 43	337 - 725	2.8 - 1.1
Supertrophic	5 - 6	12 - 31	43 - 96	725 - 1558	1.1 - 0.4
Hypertrophic	6 - 7	> 31	> 96	> 1558	< 0.4

Equations 7 to 10 can be rearranged to give expressions for Chl *a* directly in terms of TN and TP:

$$\text{Chl } a = 0.005066 \text{ TN}^{1.185} \quad (11)$$

$$\text{Chl } a = 0.163 \text{ TP}^{1.185} \quad (12)$$

Similar equations can be found in the international literature (e.g., Ryding and Rast 1989, OECD 1982, Baker et al. 1985); we have checked some of these, and they give similar results.

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Two points should be made concerning the use of these equations. The first is that they assume that lake residence time is long enough for the lakes to achieve the plankton biomass levels that can be sustained by nutrients present in the lake. Pridmore and McBride (1984) point out that for lakes with residence time less than approximately two weeks, this is not the case, and Chl *a* concentrations will be determined by concentrations upstream, as plankton are advected (transported) through the lake or reservoir. This will be the case for lakes Ruataniwha and Waitaki, which have residence times on the order of a day (Table 5), and act more like river reaches than lakes.

The second is that if measured values of TP and TN from a particular lake are used to estimate Chl *a*, it is unlikely that Equations 11 and 12 will give the same values of Chl *a*. If neither nutrient is scarce compared with the other (i.e., if they are both present in a ratio that allows balanced growth, typically TN/TP somewhere between 10 and 30; see, e.g., Wetzel 2001 or Reynolds 1984), then Equations 11 and 12 should give roughly similar answers. This is one of the underlying postulates, based on observation, for the TLI approach presented by Burns et al. (2000). On the other hand, if one nutrient is relatively scarce, that nutrient may act as a limiting factor to plankton growth, depending on the actual ratio and the physiology of the plankton.

To help assess the effects of possible nutrient limitation, bioassays were carried out on phytoplankton samples obtained from lakes Pukaki, Ohau, Ruataniwha, and the North and West Arms of Lake Benmore. The samples were incubated with different nitrogen and phosphorus treatments and their growth rates observed. Details are given in Appendix A (see also Table 3).

### 3.2. Results

Results from modelling are summarised in Table 7 and Figure 2. The results of the bioassays are given in Appendix A and will be referred to in the Discussion section to assist with interpretation of the model results.

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18/04/05

Table 7: Modelled results for in-lake concentrations

	Nitrogen - Dry land				Phosphorus - Dry land				
	Inflow load, <b>M_N_in</b> , tonnes/yr	Annual mean in-lake conc <b>TN</b> , ug/L, mg/m <sup>3</sup>	Annual mean in-lake conc <b>Chla</b> , ug/L (for N-limitation)	Trophic Level Index, N-limitation	Inflow load, <b>M_P_in</b> , tonnes/yr	Annual mean in-lake conc <b>TP</b> , ug/L, mg/m <sup>3</sup>	Annual mean in-lake conc <b>Chla</b> , ug/L (for P-limitation)	Trophic Level Index, P-limitation	In-lake TN :TP ratio
<b>Lake Tekapo</b>	18	44	0.45	1.3	0.04	4.0	0.80	2.0	11
<b>Lake Pukaki</b>	21	42	0.42	1.3	0.13	4.0	0.81	2.0	10
<b>Lake Ohau</b>	12	43	0.44	1.3	0.04	4.0	0.81	2.0	11
<b>Lake Ruataniwha</b>	101	52	0.55	1.6	0.42	4.1	0.81	2.0	13
<b>L Benmore, North Arm</b>	705	113	1.37	2.6	2.51	4.2	0.86	2.0	27
<b>L Benmore, West Arm</b>	184	165	2.15	3.1	0.47	4.3	0.88	2.1	38
<b>Lake Aviemore</b>	840	113	1.38	2.6	2.55	4.2	0.85	2.0	27
<b>Lake Waitaki</b>	830	111	1.34	2.5	2.52	4.2	0.85	2.0	26
	Nitrogen - Scenario 1				Phosphorus - Scenario 1				
<b>Lake Tekapo</b>	80	57	0.61	1.7	0.60	4.1	0.83	2.0	14
<b>Lake Pukaki</b>	94	49	0.51	1.5	1.43	4.1	0.83	2.0	12
<b>Lake Ohau</b>	56	53	0.57	1.6	0.37	4.1	0.83	2.0	13
<b>Lake Ruataniwha</b>	434	93	1.09	2.3	4.27	4.5	0.92	2.1	21
<b>L Benmore, North Arm</b>	3310	381	5.80	4.2	24.55	6.2	1.34	2.5	61
<b>L Benmore, West Arm</b>	832	604	10.00	4.8	6.07	8.1	1.81	2.9	74
<b>Lake Aviemore</b>	3920	383	5.84	4.2	26.07	6.3	1.35	2.6	61
<b>Lake Waitaki</b>	3877	371	5.62	4.1	25.78	6.2	1.33	2.5	60

		<b>Nitrogen - Scenario 2</b>				<b>Phosphorus - Scenario 2</b>				
Lake Tekapo	69	55	0.58	1.6	0.42	4.1	0.82	2.0	13	
Lake Pukaki	88	48	0.50	1.5	1.33	4.1	0.83	2.0	12	
Lake Ohau	55	53	0.56	1.6	0.32	4.1	0.83	2.0	13	
Lake Ruataniwha	206	65	0.71	1.8	1.67	4.2	0.85	2.0	15	
L Benmore, North Arm	1683	213	2.92	3.4	11.46	5.0	1.05	2.3	42	
L Benmore, West Arm	308	249	3.50	3.6	1.80	5.2	1.09	2.3	48	
Lake Aviemore	1931	209	2.85	3.4	11.60	5.0	1.04	2.3	42	
Lake Waitaki	1916	204	2.76	3.3	11.51	5.0	1.03	2.3	41	
		<b>Nitrogen - Scenario 3</b>				<b>Phosphorus - Scenario 3</b>				
Lake Tekapo	24	45	0.46	1.4	0.13	4.0	0.81	2.0	11	
Lake Pukaki	22	42	0.43	1.3	0.18	4.0	0.81	2.0	10	
Lake Ohau	34	48	0.50	1.5	0.20	4.1	0.82	2.0	12	
Lake Ruataniwha	117	54	0.58	1.6	0.99	4.1	0.83	2.0	13	
L Benmore, North Arm	935	136	1.72	2.8	5.26	4.5	0.91	2.1	30	
L Benmore, West Arm	210	182	2.42	3.2	1.12	4.8	0.98	2.2	38	
Lake Aviemore	1089	135	1.70	2.8	5.45	4.5	0.91	2.1	30	
Lake Waitaki	1078	132	1.65	2.8	5.40	4.5	0.91	2.1	30	

Results in Table 7 are grouped under eight headings, two sets for each of the four irrigation scenarios (dry land, and scenarios 1, 2, and 3). In one set of four, nitrogen is assumed to control phytoplankton growth (Equation 11), while in the second set phosphorus is assumed to control phytoplankton growth (Equation 12). Total nutrient loads from the land-use sub-regions are shown, together with predicted in-lake concentrations of TN, TP, and Chl *a*. The last column gives the ratio of TN:TP by weight for each of the lakes under the four different scenarios. Figure 1 plots the predicted Chl *a* concentrations in the table, with one plot illustrating predictions for phosphorus-controlled growth and one for nitrogen-controlled growth.

Two general observations can be made. First is that, regardless of which nutrient is assumed to control plankton growth, the impact of the three irrigation scenarios is mostly limited to the downstream lakes Benmore, Aviemore and Waitaki, with lesser impacts on the larger upstream lakes Tekapo, Pukaki and Ohau. This is consistent with the geographical distribution of the irrigation sub-regions (White et al.'s Figure 2), which are mainly downstream of lakes Tekapo, Pukaki and Ohau, as well as with the larger volumes of the three upstream lakes. In the downstream lakes the greatest impact is predicted to occur in Lake Benmore's West arm, which becomes eutrophic under Scenario 1 with nitrogen control.

The second observation concerns the discrepancy between predicted results for nitrogen control versus those for phosphorus control in the downstream lakes. All lakes remain oligotrophic according to predictions based on phosphorus control (Figure 2). The discrepancy appears to be correlated with the pattern in TN:TP ratios (Table 7), which increase markedly in the downstream lakes under Scenario 1, with progressively lesser increases under Scenarios 2 and 3. In the Discussion section this pattern in TN:TP ratios will be used in combination with the results from the bioassays (Appendix A) to explain this discrepancy.

The results from bioassays (Appendix A) indicate that under present conditions neither nitrogen nor phosphorus alone control phytoplankton growth; rather it is their combined effect that maintains the current state of oligotrophy in the lakes. The marked difference in growth response when both nitrogen and phosphorus were added to the incubation, compared with the cases of addition of either nutrient alone, is the most notable result that emerged from the bioassays. The present state of "co-limitation" is of importance when trying to resolve the apparent contradiction between the model predictions for algal biomass based on equations that account either for nitrogen control alone or phosphorus control alone, but not a combination of the two. It will be considered further in the Discussion section.

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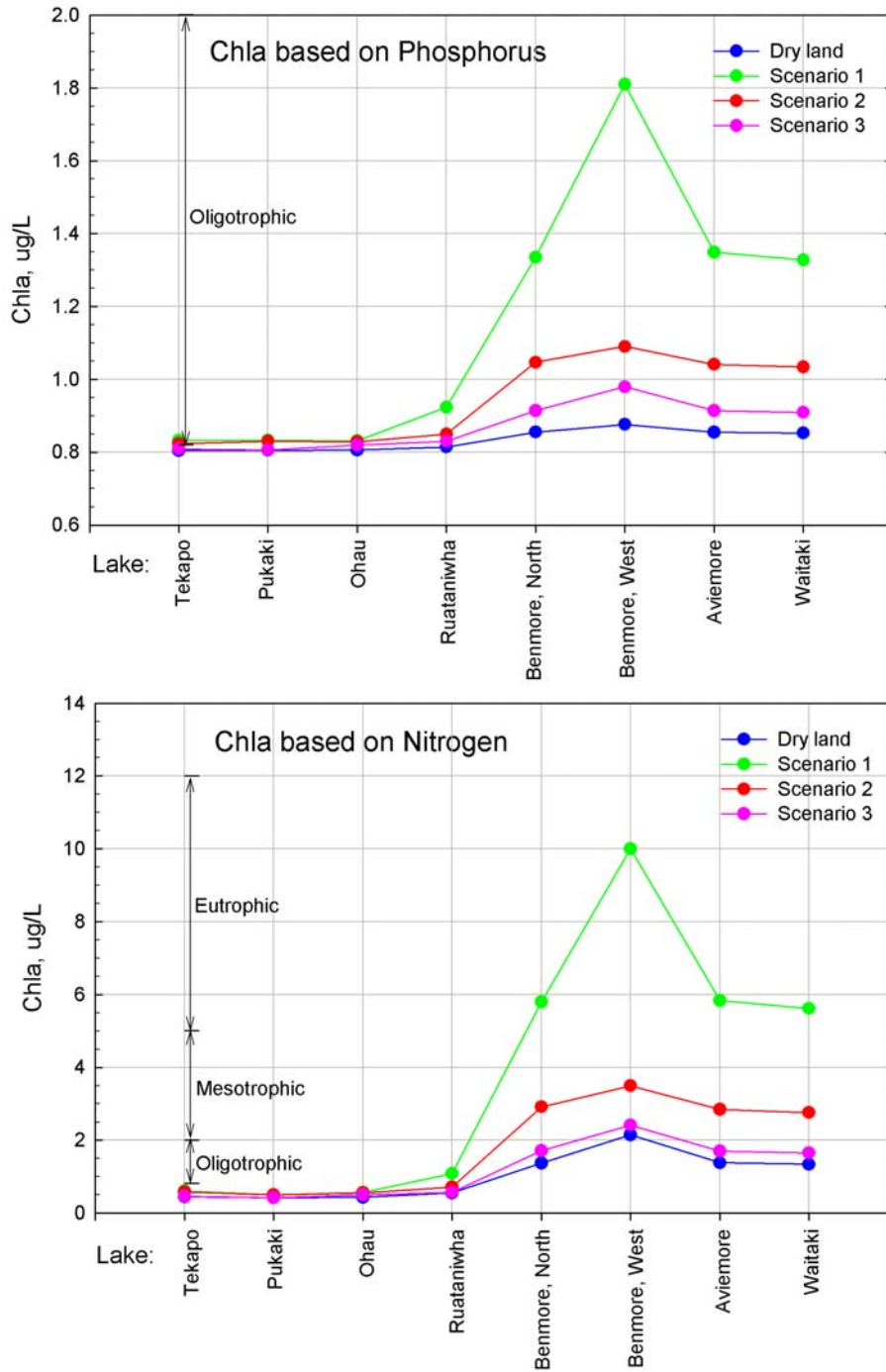


Figure 2: Chlorophyll *a* concentrations predicted under different irrigation scenarios and for either phosphorus or nitrogen control of phytoplankton production. Trophic class boundaries are those specified by Burns et al. (2000) and given in Table 6.

### 3.3. Discussion

This section includes discussion of results from modelling and from field surveys, including the bioassays described in Appendix A as well as previous relevant field work. The discussion represents an effort to place the modelling and bioassay results in the context of the ecology of the complete lake flora. It starts with an introductory section that provides a framework in which to view the results, and is followed by a section describing present conditions. The remaining sections focus on the model results for phytoplankton biomass, and include brief consideration of the implications of model nutrient predictions for submerged macrophytes.

#### 3.3.1. In-lake biological response

Phytoplankton (free-floating algae), epiphytic algae (attached to plants), epilithic algae (attached to inert substrata) and submerged macrophytes constitute the primary producers in aquatic systems. Their growth is dependent on a number of factors including, but not exclusive to, light availability, nutrient availability, substrate suitability and wave exposure. Of these factors, the two most important in terms of limiting photosynthesis, and hence growth potential, are light and nutrient availability. For example, in a turbid lake, reduced light availability can limit photosynthesis regardless of the quantity of nutrients available, while in a clear oligotrophic lake, where light is not limiting, nutrients, in particular nitrogen and phosphorus, may be in short supply (Rattray *et al.* 1991).

Light availability in lakes Tekapo and Pukaki is restricted by the presence of relatively high concentrations of very fine suspended mineral particles (glacial flour) carried into the lakes by rivers draining glaciers upstream. Much of this suspended material is trapped within the two lakes, and water transparency increases downstream. Hence light limitation is an issue of importance in lakes Tekapo and Pukaki, but much less so downstream, where phytoplankton production is limited mainly by availability of nutrients.

It should be noted that the model predictions are based only on nutrient levels and do not account for possible light limitation. Hence they may overestimate productivity in lakes Pukaki and Tekapo (e.g., compare Chl *a* predictions in Table 7 for lakes Pukaki and Tekapo with the single observations in Table 3) . However, model results predict practically no impact on these upstream lakes for any of the scenarios, regardless of which nutrient is assumed to control production. Hence this shortcoming of the model does not have any effect on conclusions drawn from the model results, and will not be considered further.

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### 3.3.2. Present conditions in the Waitaki lakes

#### Phytoplankton

Currently phytoplankton growth in all seven lakes falls within the range of 0.2 to 2  $\mu\text{g L}^{-1}$  chlorophyll *a* (Chl *a*), placing these lakes in the ultra-microtrophic to oligotrophic range (see Table 6). Chl *a* concentrations show an increasing trend moving down the lake system as water clarity increases (present study, NIWA data unpublished). Diatoms (for example *Asterionella* sp, *Cyclotella* sp, *Fragilaria* sp) and unicellular green algae (for example *Chlorella* sp, *Synechococcus* sp) dominate the phytoplankton communities.

#### Periphyton (including epiphytic and epilithic algae)

In the upper Waitaki lakes (lakes Tekapo, Pukaki and Ohau) periphyton is predominantly controlled by wave action and water level fluctuations (NIWA data, unpublished). LAKEWAVE exposure modelling indicates that for lakes Tekapo and Pukaki over 90% of the shoreline is too exposed for periphyton development, while 65% of the shoreline in Ohau is also unsuitable (NIWA data, unpublished).

For lakes Ruataniwha, Benmore, Avimore and Waitaki periphyton development is extensive (author's personal observations) with thick layers of epilithic and epiphytic algae present in all suitable habitats in all four lakes. LAKEWAVE models indicate that wave exposure is not the main regulator for periphyton in these lakes.

#### Submerged macrophytes.

As with periphyton development, the presence of submerged macrophytes in lakes Tekapo, Pukaki and Ohau is primarily controlled by wave exposure and water level fluctuations. LAKEWAVE exposure modelling predicts that wave exposure in lakes Tekapo and Pukaki prevents macrophyte establishment throughout the entire lake, while approximately 35% of the shoreline of Lake Ohau is suitable for macrophyte growth (NIWA data, unpublished). Lake wide macrophyte surveys conducted throughout the last 20 years confirms these predictions (NIWA Plant database, unpublished).

Lakes Benmore, Avimore and Waitaki presently support a rich community of submerged macrophytes. Dense beds of macrophytes are present in all available locations in these three lakes. Recently dense beds of the problematic weed, *Lagarosiphon major*, have been found in Lake Benmore throughout the west arm and down the neck region (Sutherland 2004). Currently, Landward Management and Meridian Energy Ltd are undertaking an active control programme.

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18/04/05

### 3.3.3. Model predictions for Chl *a*

It was noted in the Results section that, regardless of which nutrient is assumed to control plankton growth, the impact of the three irrigation scenarios is mostly limited to the downstream lakes Benmore, Aviemore and Waitake, with minimal impacts on the larger upstream lakes Tekapo, Pukaki and Ohau (Table 7 and Figure 2). This is true for Chl *a* concentrations, nutrient concentrations, and for the ratios of TN to TP (Table 7 and Figure 2). The reasons for this seem to be relatively straightforward, and due mainly to the geographical distribution of the irrigation sub-regions (White et al.'s Figure 2), which are mainly located downstream of lakes Tekapo, Pukaki and Ohau. A further factor is the relatively larger volumes of these upstream lakes, which provide for increased dilution of the loads that do enter the lakes.

Much less straightforward, and requiring further discussion, is the discrepancy between predicted Chl *a* concentration results for nitrogen control versus those for phosphorus control in the downstream lakes. Both sets of predictions exhibit similar patterns in terms of the relative impacts on the different lakes. Both predict that the West Arm of Lake Benmore will be most severely affected, with the Northern Arm less so. The effects are then propagated downstream to the smaller lakes Aviemore and Waitaki, which are predicted to have similar phytoplankton growth potential to that of the North Arm. However, impacts are much more severe, in absolute terms, when using nitrogen to predict Chl *a* concentrations than when using phosphorus. Lake Benmore's West Arm becomes eutrophic under Scenario 1 with nitrogen control, with concentrations of Chl *a* comparable to those found in lakes Rotoiti (North Island), Johnson and Hayes, as illustrated in Figure 2 of Viner and White (1987). Lake Benmore's North Arm, Lake Aviemore and Lake Waitaki also fall into the eutrophic class for Scenario 1 with nitrogen control, and are mesotrophic under Scenario 2. In contrast, all lakes remain oligotrophic if it is assumed that phytoplankton growth is controlled by phosphorus alone.

The results from bioassays (Appendix A), however, indicate that under present conditions neither nitrogen nor phosphorus alone control phytoplankton growth. Little growth response was obtained in the incubations when either nutrient was added alone. In contrast growth rates increased markedly when both nutrients were added together. This condition of "co-limitation" is consistent with present N to P ratios in the lakes, which are in the general range of 10 to 30 (Table 3; Table 7, dry land scenario).

The discrepancy between model predictions based on either N or P is greatest for those cases in which the ratios of TN/TP exceed 30. It is often assumed in such cases that growth will be limited by phosphorus availability, and hence predictions based on

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phosphorus control should be chosen in preference to those based on nitrogen control, although such limits are variable in lakes (e.g. Wetzel 2001, p.278). We believe, however, that the results based on phosphorus control seriously under-predict the likely impacts on the lakes, for two reasons. One is the marked result from the bioassays, which show unequivocally that if both nitrogen and phosphorus are added to the lakes together (the case under the irrigation scenarios), growth will greatly exceed that which would occur if only one nutrient were added (the case to which the model equations apply). The second reason is that several lake phytoplankton species have an ability to store phosphorus, and can thereby greatly optimise their use and uptake of this nutrient and circumvent its limiting effects to some extent.

The true response will probably be somewhere in between the responses predicted in the two sets of graphs in Figure 2. However, we believe it will be closer to the predictions based on nitrogen loads. If forced to choose between the sets of predictions in order to provide a basis for management decisions, we would recommend the predictions based on nitrogen loads. In either case, the model results provide a warning of possible impacts on lakes Benmore, Aviemore and Waitaki of increases in nutrient loads.

#### 3.3.4. Waitaki Lakes Future Scenario

##### Phytoplankton

Based on the predictive model for Chl *a* for nitrogen (Figure 1) phytoplankton growth in lakes Tekapo, Pukaki, Ohau and Ruataniwha are not likely to exceed oligotrophic levels under all three scenarios. Predicted increases in Chl *a* concentration in lakes Benmore (North and West arm), Aviemore and Waitaki under Scenarios 2 and 1 reach mesotrophic and eutrophic levels, respectively. Such a shift in trophic status is likely to have major implications for the foodweb dynamics of the lake. Aesthetically, there is likely to be a green colouration to the water during periods of peak growth (mid summer). Increases in nutrient input are likely to result in a shift in species dominance promoting the growth of weedy or undesirable taxa.

##### Periphyton (including epilithic and epiphytic algae)

As with the increase in phytoplankton growth, periphyton is likely to increase with the additional supply of nutrients. Thick mat-like structures, containing algae embedded in thick mucilage, already carpet the substrate in lakes Benmore, Aviemore and Waitaki and are predicted to increase in biomass. As the periphyton increases in biomass large fragments can slough off (as a result of wind-driven events or other forms of disturbance). In early May 2003, the Benmore power station experienced an algal problem on the Aux units. Thick mucilaginous mats of algae (comprised mainly of

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diatoms) were drawn into the units and daily cleaning of these units was required (Sutherland 2003). Prior to the algal bloom occurring the Ahuriri Delta region of the West arm, Lake Benmore, was sprayed with the aquatic herbicide, Diquat (27 March 2003) in an effort to control *lagarosiphon*. Diquat was effective in killing off the above-ground biomass in the treatment zone (Johnstone 2003). During growth macrophytes accumulate a large amount of nutrients, which are released to the sediment and water column when the macrophyte dies (Asaeda et al 2000). The release of ammonia and phosphate from decaying macrophytes was found to be in concentrations sufficient to promote algae growth (Rho and Gunner 1978). It is, therefore, plausible to suggest that following the successful treatment with Diquat sufficient nutrients were released to stimulate the algal bloom six weeks later. As there is no nutrient data from Lake Benmore following the macrophyte decay, the scale of this bloom cannot be placed in context with the proposed nutrient loadings under the three scenarios. However this event is indicative of the kind of problems that can be experienced under excessive growth of periphyton from nutrient loading.

#### Macrophytes

Growth rates of macrophytes vary between species with weedy, problematic species typically capable of faster growth than desirable species. As macrophytes are capable of deriving their nutrients from both sediment and surrounding waters, an increased loading of nutrients into the lakes may favour excess growth of macrophytes. As mentioned above, macrophyte growth in lakes Tekapo and Pukaki is unlikely to occur. For the other lakes the promotion of weedy macrophyte growth could lead to the formation of dense canopies at, or near, the water surface. This in turn can lead to the displacement of native macrophytes, thus reducing biodiversity; impede recreational activities, such as boating, fishing and swimming; and impact on hydro-electricity operations.

At the other end of the spectrum, excessive accumulation of epiphytic algae on the macrophytes may smother the macrophytes and subsequently result in a decline in vegetation.

### **3.4. Conclusion**

For lakes Benmore (North and West arm), Aviemore and Waitaki, our model predicts that, based on the nutrient loading forecasts, phytoplankton growth, as determined by chlorophyll *a*, will reach eutrophic and mesotrophic status for scenarios 1 and 2, respectively. Increases in nutrient inputs to the primary producers in these lakes may result in:

- Formation of algal blooms, resulting in discolouration of the water during period of peak growth (mid summer).

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18/04/05

- Shift in dominant species (for phytoplankton, periphyton and macrophytes) to weedy, or undesirable species.
- Displacement of sensitive species resulting in loss of biodiversity.
- Vegetation decline due to smothering by algae.
- Loss of aesthetic values and impeded recreational activities.
- Economic loss through impediment of hydro-electrical generation from excessive macrophyte or periphyton growth blocking intacts.

Due to other controlling factors, such as light availability, substrate suitability, wave exposure and water level fluctuations, the proposed nutrient loading rates are unlikely to impact on the growth of phytoplankton, macrophytes and periphyton in lakes Tekapo, Pukaki and Ohau.

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18/04/05

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## Appendix A.

### Introduction:

Bioassay experiments to determine the effects of nitrogen and phosphorous additions, both singly and in combination, on the growth of natural phytoplankton populations within the upper Waitaki lakes were carried out in the laboratory. The primary purpose of these assays was to determine which nutrients are limiting to the production of algae in the lakes of the upper Waitaki system for the assistance of interpreting results generated from the predictive model.

### Methods:

20 L water samples containing natural populations of phytoplankton were collected from each of the following lakes: Ohau, Pukaki, Ruataniwha, Benmore – Ahuriri (West) Arm, and Benmore – Haldon (North) Arm, during August 2004. The water containers were kept cool and transported back to the laboratory. 1L aliquots of water were transferred into sterile 1.25L clear bottles and one of the following treatments were applied to each bottle:

1. Nitrogen (as  $\text{NaNO}_3$ ),  $200\mu\text{g L}^{-1}$  N
2. Phosphorus (as  $\text{K}_2\text{HPO}_4$ ),  $20\mu\text{g L}^{-1}$  P
3. Nitrogen and phosphorus ( $200\mu\text{g L}^{-1}$  N and  $20\mu\text{g L}^{-1}$  P)

Bottles containing the various lake waters without nutrient additions were kept as controls. Bottles were incubated for 7 days at  $12^\circ\text{C}$  under cool-white fluorescent tubes with a 12:12 hour light: dark photoperiod and were routinely shaken 3 times a day to prevent algae adhering to the sides. All assays were carried out in triplicate.

Chlorophyll *a*, used as a measure of biomass, was determined fluorometrically on a Perkin-Elmer Fluorometer, following cold extraction in 90% acetone. Background chlorophyll *a* was also determined from fresh lake samples.

### Results and Discussion:

The effects of the addition of the various nutrients, relative to the controls, on the growth (as determined by chlorophyll *a* concentrations) of natural phytoplankton populations from the four lakes is shown in Figure 3. While the addition of nitrogen or phosphorous singly did not stimulate algal growth above that of the control, the

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addition of both nutrients simultaneously caused an increase in growth rate that ranged between 10 (Lake Pukaki) and 40 fold (Ruataniwha) in all the lakes (Figure 3 a-e).

The results from the bioassay indicate that all four lakes (two arms in Lake Benmore) are co-limited by nitrogen and phosphorus. The addition of either nutrient did not stimulate growth above that of the control or the baseline lake values. However, the addition of both nutrients stimulated considerable growth of the phytoplankton. Nitrogen and phosphorus concentrations used in the bioassay experiment were at 200  $\mu\text{g L}^{-1}$  and 20  $\mu\text{g L}^{-1}$ , respectively. Under the proposed loading scenarios the concentration for nitrogen was comparable to annual mean in-lake concentrations predicted for lakes Benmore (North and West arm), Aviemore and Waitaki (Table 7). However, the phosphorous concentrations used in the bioassay were 2.5 – 5 times higher than maximum predicted concentrations for all three scenarios.

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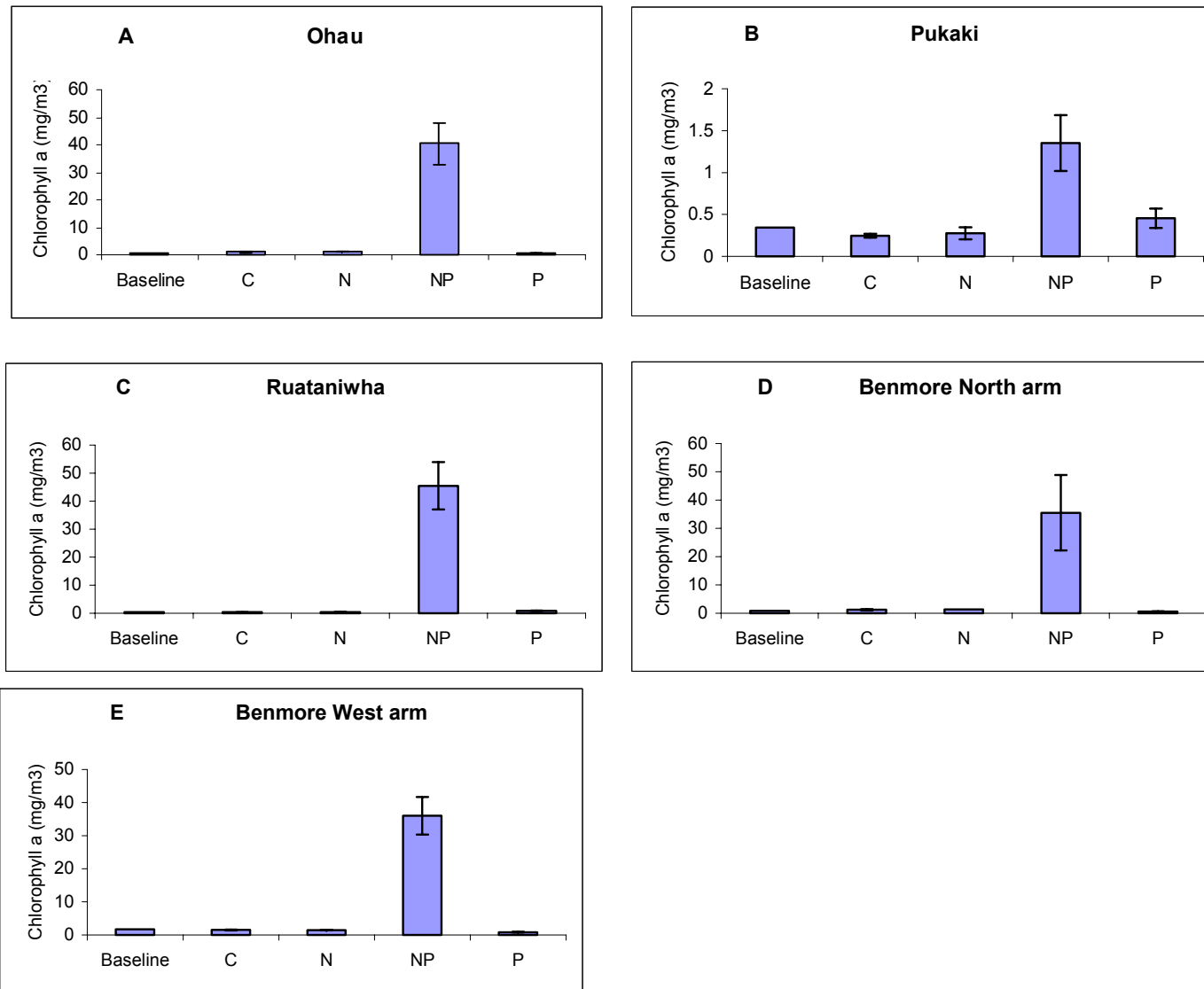


Figure 3. Effects of nutrient additions to the growth of natural phytoplankton populations from A) Lake Ohau; B) Lake Pukaki; C) Lake Ruataniwha; D) Lake Benmore, North arm; E) Lake Benmore, West arm. Baseline = background levels, C = control, N = nitrogen added, P = phosphorus added, NP = nitrogen and phosphorus added.