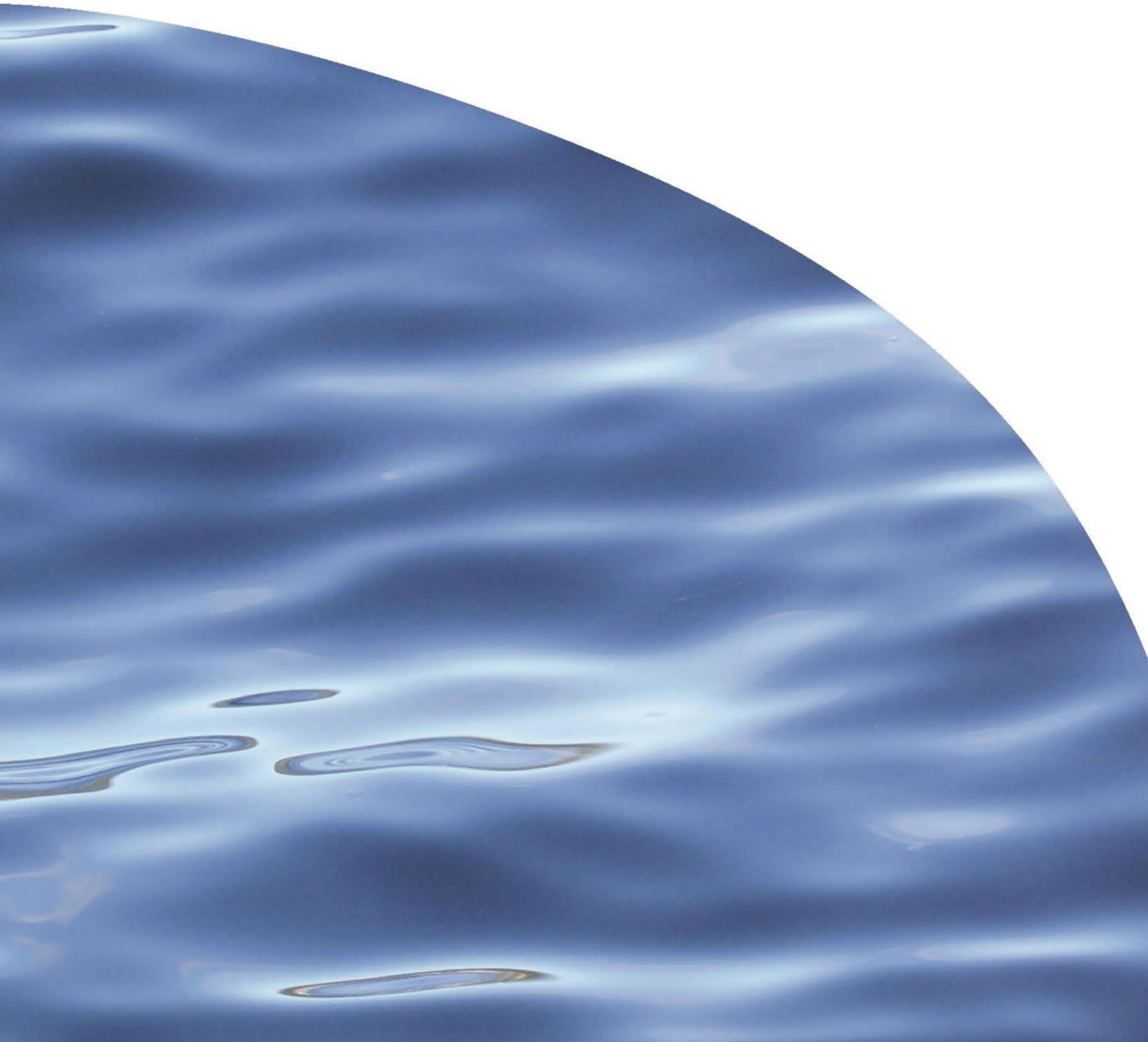
REPORT NO. 3589

UPDATING CLUES NUTRIENT LOAD PREDICTIONS FOR ASHBURTON BASIN AND WAIMAKIRIRI HIGH-COUNTRY LAKES



UPDATING CLUES NUTRIENT LOAD PREDICTIONS FOR ASHBURTON BASIN AND WAIMAKIRIRI HIGH-COUNTRY LAKES

DAVID KELLY, LISA FLOERL, PAULA CASSANOVAS

Prepared for Department of Conservation and Environment Canterbury

CAWTHRON INSTITUTE
98 Halifax Street East, Nelson 7010 | Private Bag 2, Nelson 7042 | New Zealand
Ph. +64 3 548 2319 | Fax. +64 3 546 9464
www.cawthron.org.nz

REVIEWED BY:
Simon Stewart

APPROVED FOR RELEASE BY:
Joanne Clapcott

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EXECUTIVE SUMMARY

This report updates a previous 2014 Cawthron study that calculated the predicted catchment loads of total nitrogen (TN) and phosphorus (TP) to 25 Canterbury high-country lakes using the Catchment Land Use for Environmental Sustainability (CLUES) model. This study updates the catchment load predictions for 8 Ashburton basin lakes and 5 Waimakiriri lakes using an updated version of CLUES (Version 10.6), taking into account the most recent information on landcover vegetation and updated bird population monitoring data to predict total N and P loads to lakes. From this comparison, we make recommendations based on using updated CLUES data for assessing catchment load limits for the 13 lakes, and a mass balance model approach to calculate loads reductions required to meet policy objectives for TN, TP and chlorophyll-*a* concentration. Model findings are expected to be considered when setting catchment nutrient load targets for the Canterbury high-country lakes, as well as to inform management on what specific lakes may be affected by other nutrients sources such as internal nutrient cycling from the lakebed, wind-suspension of sediment in shallow unvegetated lakes and groundwater inflows, not inherently accounted for by the CLUES catchment model.

The updating of nutrient load predictions for a subset of 13 Ashburton and Waimakiriri lakes using CLUES 10.6 appears to provide reasonably consistent predictions of in-lake TN and TP for most high-country lakes relative to modelling work conducted in 2014. Overall, CLUES 10.6 was more likely to predict higher nutrient loads to lakes than the previous version (CLUES 10.2) used in the 2014 study, particularly for shallow lakes. Reasons for this are not fully understood as there were no significant changes in catchment landcover between the two study periods. Updated load predictions resulted in higher residuals of modelled to measured lake median TN concentrations for 4 lakes (Lakes Hawdon, Emma, Denny and Clearwater), and these should be examined in greater detail, possibly related to groundwater or internal nutrient cycling. Updated calculations of P loads using CLUES 10.6 appears to have provided good predictions of in-lake TP for deep lakes, but tended to overpredict in-lake TP concentration for a number of shallow lakes (Lakes Emma, Denny). Greater variability in TP concentrations in shallow lakes associated with wind resuspension and nutrient recycling generally means that TP is harder to accurately model using only catchment loads in shallow lakes.

Estimates of load reductions required to reduce in-lake water quality conditions from their 5-year (2015–2020) mean levels of TN, TP and chlorophyll-*a* to those meeting objectives in the Canterbury Land and Water Plan were conducted using the calibrated mass balance models. They suggest that considerable reductions in catchment nutrient loads are required to achieve the current plan targets for several lakes. Five of 9 lakes considered required large (> 66%) reductions in catchment N loads to meet their plan objectives, whereas 2 required moderate (34–66%) or small (< 33%) reductions to meet plan objectives. Two of 10 lakes considered required large reductions in catchment P loads to meet their current plan objectives, and 3 required moderate or small reductions in loads to meet plan objectives. Six of 10 lakes required large reductions in nutrient loads to meet chlorophyll-*a* objectives, and 4

required either moderate or small load reductions. Overall, the predictions of load changes are thought to be more robust for deep lakes than for shallow lakes, largely due to the greater certainty in model predictions of in-lake nutrient concentrations for deep lakes.

Uncertainty associated with model predictions included: unaccounted-for sources of nutrients from lake internal recycling and groundwater inputs; uncertainty associated with waterbird nutrient loads; phytoplankton community differences between lakes; and seasonality of lake monitoring data.

Model results from this study are considered appropriate for use in lake management in combination with other sources of data on farm-scale nutrient losses (Overseer predictions) and inflow monitoring. Further site-specific investigations on in-lake processes (e.g., nutrient recycling from the lakebed), groundwater nutrient inputs, and phytoplankton dynamics (including n-fixation) could improve nutrient source quantification.

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1. INTRODUCTION

1.1. Background

The Canterbury region supports some of the most outstanding examples of high-country lakes in New Zealand. Conservation of their natural heritage values, recreational values and cultural values requires an understanding of their vulnerability to different pressures, including land use change.

The implementation of the National Policy Statement (NPS) for Freshwater Management (Ministry for the Environment 2020) requires regional authorities to establish and implement limits to protect water quality and ecological values of waterbodies in their region. In Canterbury, as in many parts of New Zealand, the primary land uses involve agriculture. The management of nutrient losses from farmland is expected to be a critical component of maintaining ecological and other (recreational, aesthetic) values of lakes. As such, understanding ecological responses of waterbodies to nutrient loading is essential in a regional planning context for setting nutrient loads to lakes and for the conservation of freshwater ecosystems.

The establishment of nutrient-sensitive lake zones by Environment Canterbury in their Land and Water Regional Plan has been a significant step towards recognising the importance of these waterbodies to the region and their sensitivity to land use change. Further monitoring and technical investigations aimed at understanding trends in water quality as well as drivers of change in these waterbodies has been undertaken to manage lakes in these sensitive lake zones (Bayer & Meredith 2020).

The Department of Conservation (DOC) has identified Ō Tū Wharekai (Ashburton Basin and upper Rangitata River) as a key freshwater conservation site under the Arawai Kākāriki programme of work. Department of Conservation has gained management responsibility for a considerable area of land in the basin following tenure review and other processes. They aim to work with all landowners towards protecting and enhancing values of the Ashburton Basin. Restoration and monitoring actions for this catchment area are based on the best available science and from gathering new information on freshwater values and threats. Therefore, the aim of this study, funded under Arawai Kākāriki, is to inform long-term management strategies based on a better understanding of the relationships between nutrient loading, nutrient status of lakes, and associated ecological values of the waterbodies.

In 2013–2014, Cawthron Institute was contracted by DOC and Environment Canterbury to conduct a study calculating the predicted catchment loads of total nitrogen (TN) and phosphorus (TP) to 25 Canterbury high-country lakes using the Catchment Land Use for Environmental Sustainability (CLUES) model (Kelly et al. 2014). The study then used predicted nutrient loads to compare against in-lake water quality monitoring data (2009–2014 median TN and TP concentrations) to calibrate a mass balance Vollenweider model characterising the relationship between nutrient loads and in-lake water quality for the 25 lake set. Water quality and ecological health data collected between 2009 and 2014 were also compared against predicted catchment loads to evaluate relationships between lake ecological health and nutrient loads. The study concluded that the CLUES model largely resulted in good statistical relationships between total nitrogen (TN) and total phosphorus (TP) loads and in-lake nutrient concentrations. The relationships were improved by transforming nutrient loads with Vollenweider regression models, which took into account physical features of the lakes (e.g. maximum depth, water residence time). The nutrient loads estimates for Canterbury high-country lakes were also correlated with other variables of ecological integrity.

Since the completion of this study 6 years ago, further updates in the CLUES modelling platform have been made, and underlying model components (particularly Overseer), have been updated by NIWA and AgResearch, the owners of the model. Similarly, water quality monitoring of the Canterbury high-country lakes by Environment Canterbury and inflow streams by DOC has continued to be undertaken, and therefore updated data sets are now available for re-evaluating the mass balance model developed in 2014.

1.1.1. Purpose of this report

The Department of Conservation and Environment Canterbury requested that Cawthron Institute update some of the modelling work conducted in 2014 focussing on predicting nutrient loads to Canterbury high-country lakes. Specifically, we were asked to update the catchment load predictions for 8 Ashburton basin lakes and 5 Waimakiriri lakes using an updated version of CLUES (Version 10.6). This modelling took into account the most recent information on landcover vegetation and compared it to updated information on in-lake nutrient concentrations and stream inflow nutrient concentrations. From this comparison, we were to make recommendations on whether the nutrient retention model developed in 2014 for 25 high-country lakes can be utilised to quantify relationships between updated nutrient load and in-lake water quality.

Specifically, the objectives of the study were to:

- update a catchment nutrient load modelling for 13 high-country lakes using the CLUES 10.6 model taking into account the most recent data on landcover information using Land cover database V5 (Landcare Research)
- update predictions of waterbird nutrient load contributions to Ashburton Basin lakes (previously conducted in 2014) taking into account long-term population trend monitoring data collected by DOC.
- evaluate the nutrient mass-balance model developed in 2014 in terms of its applicability to updated CLUES 10.6 catchment load data for the 13 updated lakes.

- calculate TN and TP loads using the mass balance model to meet Environment Canterbury regional plan standards for TN, TP and chlorophyll-*a* (chl-*a*) concentration in the 13 lakes.

Model findings are expected to be considered in the context of using CLUES catchment load predictions in the wider process setting catchment nutrient load targets for the Canterbury high-country lakes. The findings will also inform management on what specific lakes may be affected by other nutrients sources and processes such as internal nutrient cycling, wind-resuspension and groundwater inflows, not inherently accounted for by CLUES catchment model.

2. MODELLING APPROACH

Methods to assess predicted catchment nutrient loads against water quality patterns in 27 Canterbury high-country lakes were described in detail in Kelly et al. (2014).

Updated data sets of nutrient loads and in-lake variables were confined to 13 high-country lakes in the upper Waimakariri and Ashburton basins, which have long-term (i.e., > 15 years) water quality data sets and are of high community use and concern. To quantify annual nutrient loads to the 13 lakes, we used the national Catchment Land Use for Environmental Sustainability[1] V10.6 (CLUES) model (Woods et al. 2006) to predict loads of total phosphorus (TP) and total nitrogen (TN). The model was calibrated to lake water quality and ecological monitoring data for up to 13 lakes.

Vollenweider models from the original Kelly et al. (2014) study were used to fit regression models to predicted nutrient loading and water quality data (Vollenweider 1982). At present there are only limited environmental monitoring data for nutrient loading from lake tributaries in this region, therefore a catchment modelling approach was used predicting nutrient loads. Some sensitivity analyses were conducted using stream inflow monitoring data to evaluate predicted mean annual nutrient concentrations made by CLUES at 10 stream reaches in the lake catchments of focus.

This report brings together the findings of the modelling across the gradient of catchment nutrient loading, and recommends possible approaches to using this information for setting nutrient loads for Canterbury high-country lakes. The diagram below (Figure 1) provides an overview of the study approach, indicating the input data, modelling, and other assessments undertaken.

[1] http://www.mpi.govt.nz/environment-natural-resources/water/clues

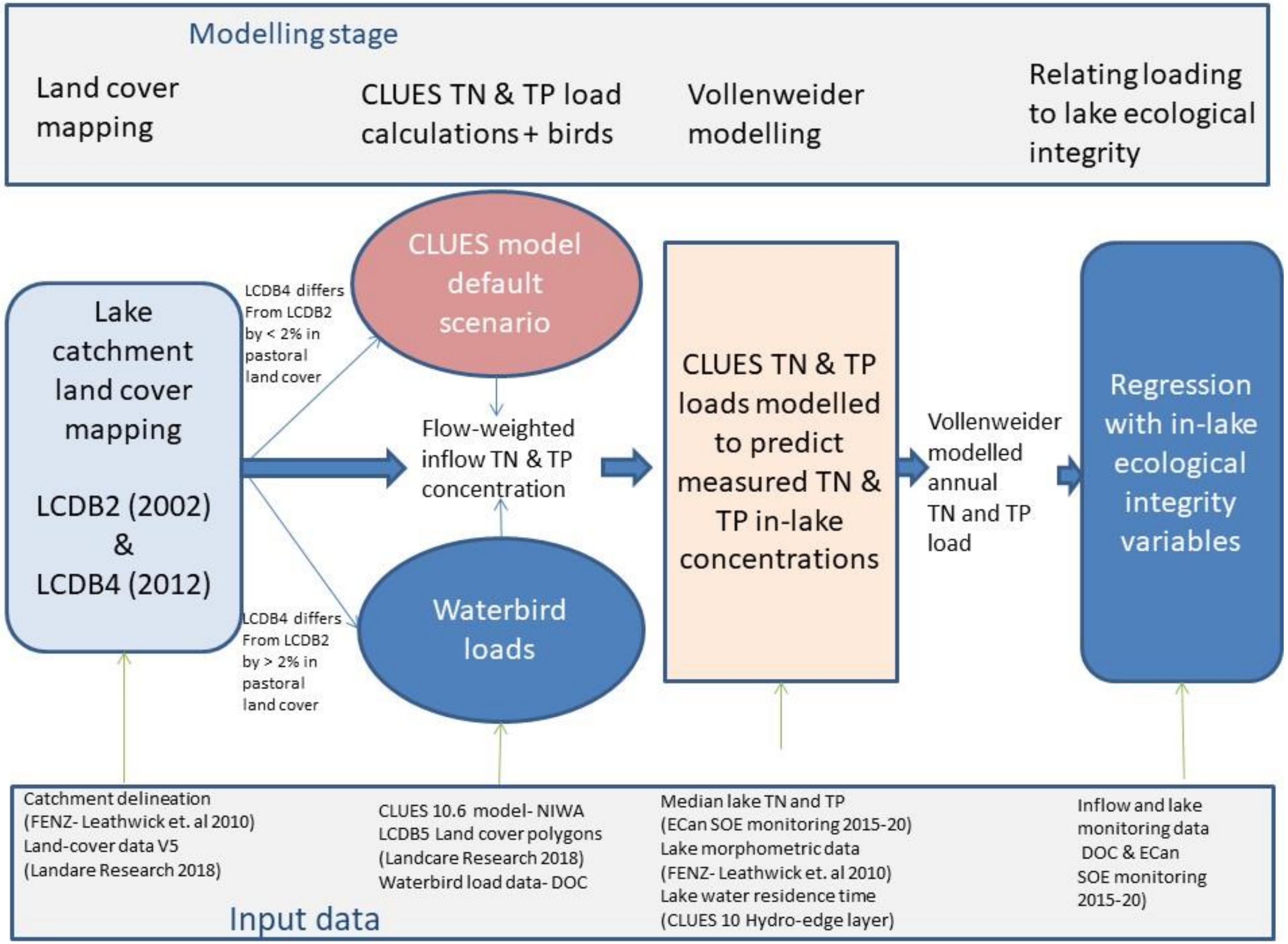


Figure 1. Diagram of the stages of modelling processes followed in this study and associated input and output data for the modelling components.

2.1. Land cover mapping

Lake catchment localities and land cover maps for the 13 lake catchments are shown in Figures 2 to 6, and the proportional amounts of land cover from the Land Cover Database (LCDB v5.0) are given in Table 1. Lake catchment boundaries were derived from the Freshwater Ecosystems of New Zealand (FENZ; Leathwick et al. 2010) and overlaid with land cover information from Land Cover Database version 4.0 (Landcare Research 2014).

The 13 study lakes varied in their land cover attributes; importantly, in their relative proportions of catchment areas in agriculture, forestry, native forest or native grassland, thereby providing a gradient of nutrient loading to assess against in-lake response measures.

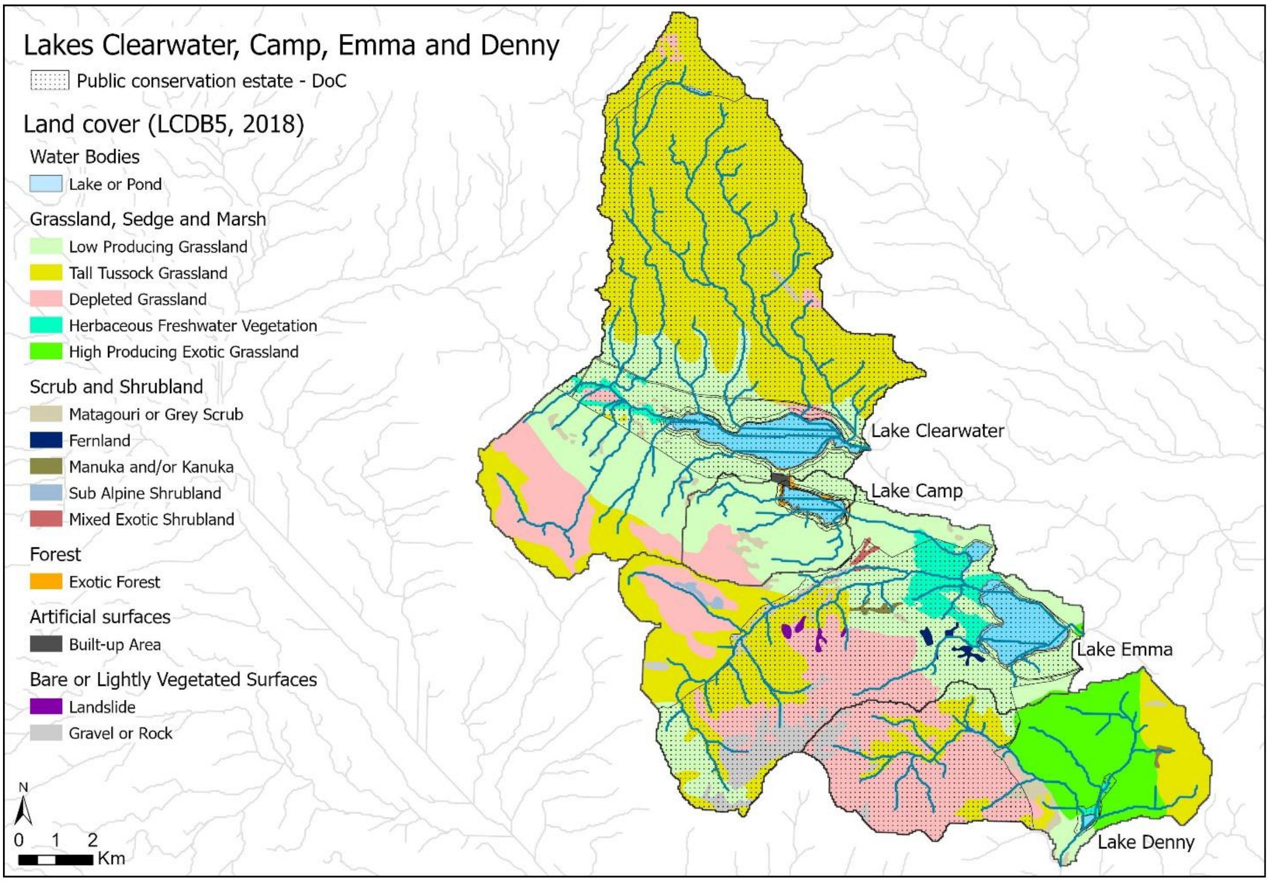
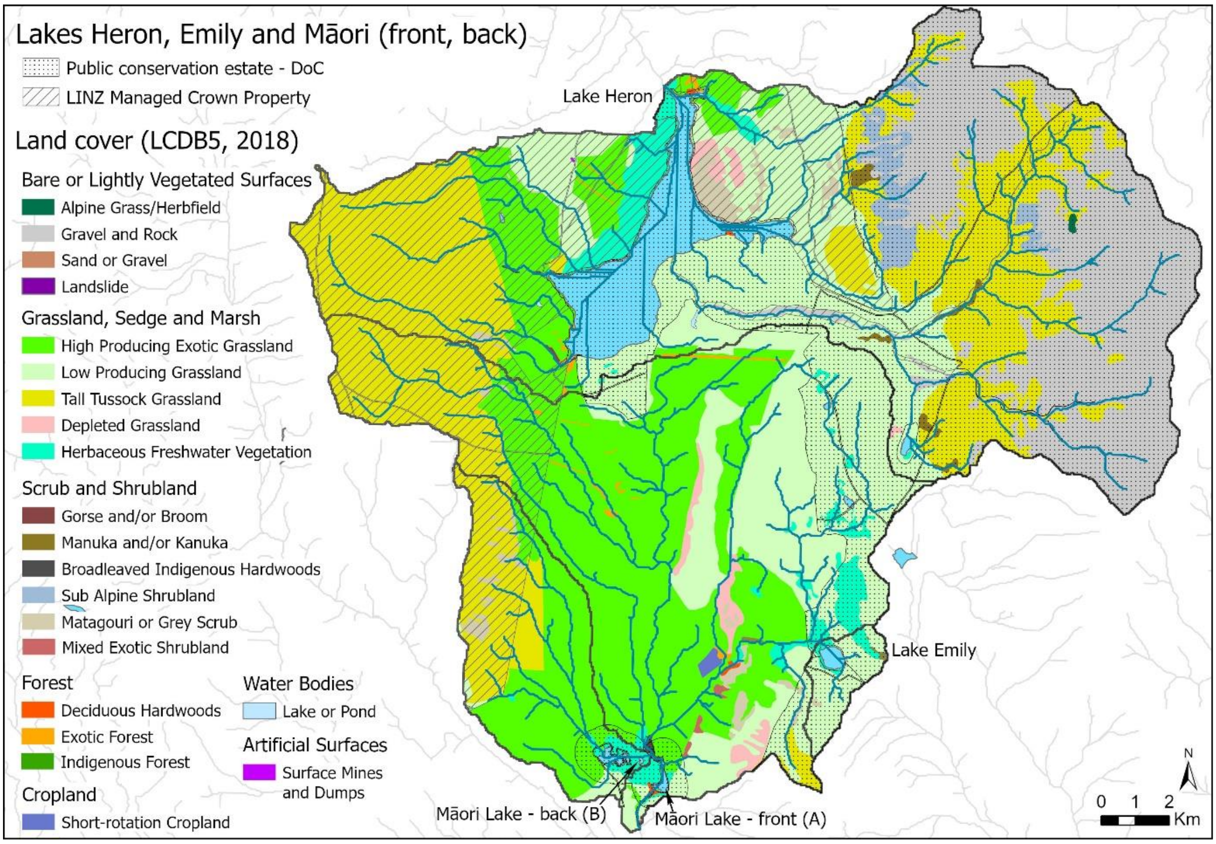


Figure 2. Lake catchment land-cover vegetation (Land Cover Database version 5.0) for four lakes in the Ashburton Basin, South Canterbury.



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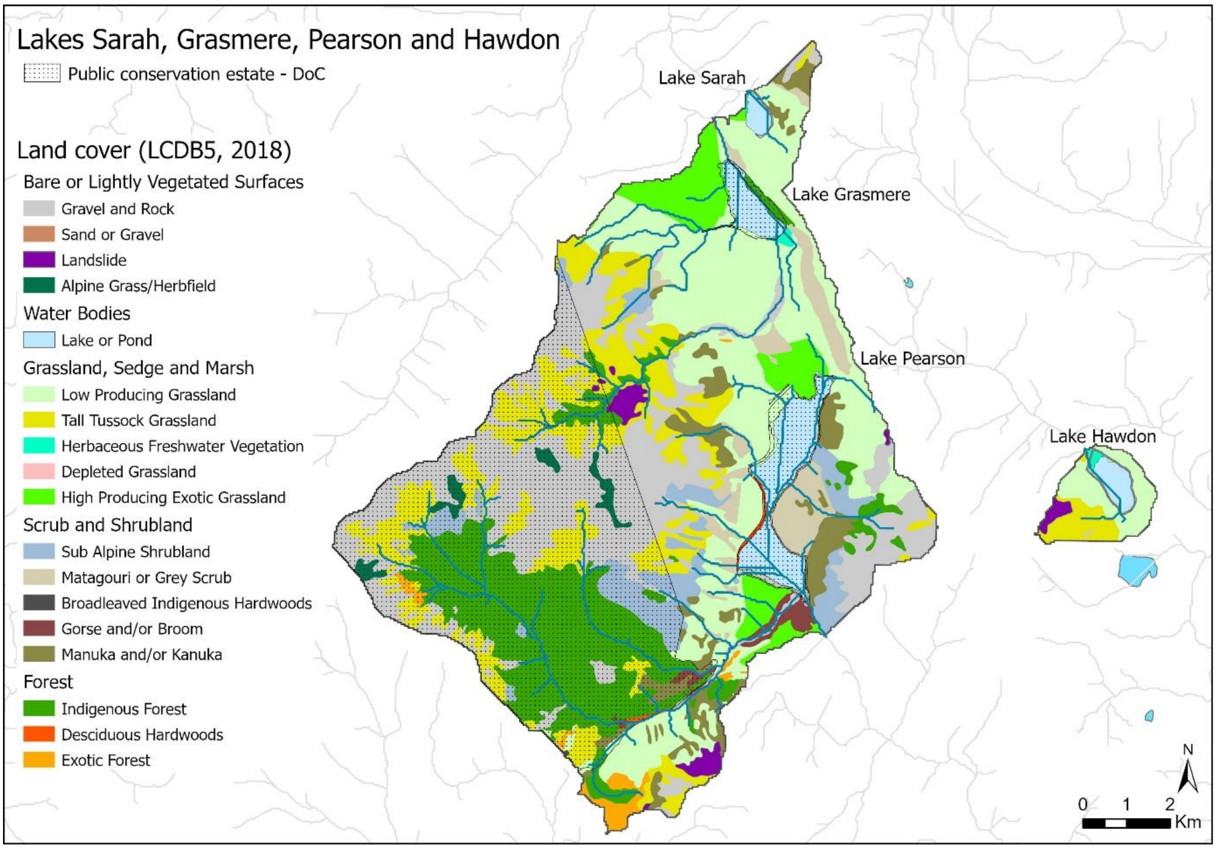


Figure 4. Lake catchment land-cover vegetation (Land Cover Database version 5.0) for four lakes in the Upper Waimakiriri Basin, North Canterbury.

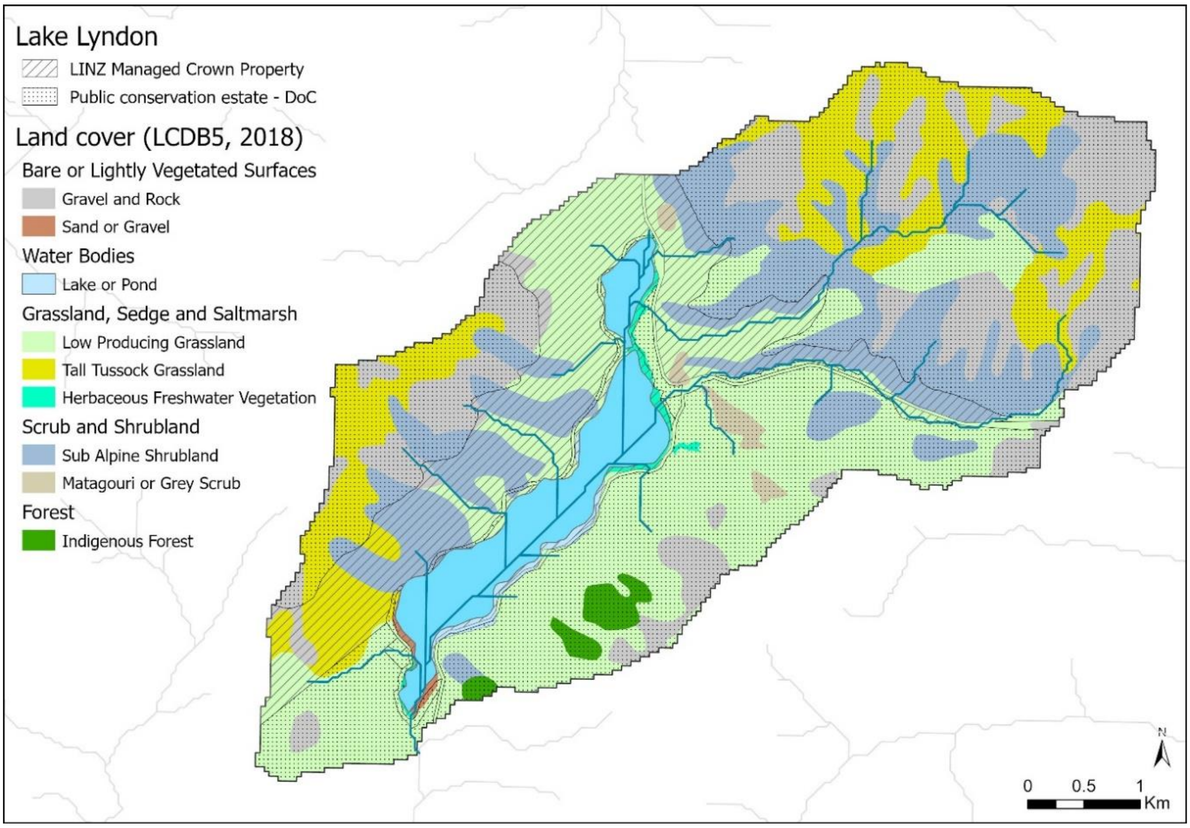


Figure 5. Lake catchment land-cover vegetation (Land Cover Database version 5.0) for Lake Lydon in the Upper Waimakiriri Basin, North Canterbury

Table 1. Proportional coverage (and percent change since 2012) in catchment production land cover for 13 Canterbury high-country Lakes in 2018 as reported in LCDB5 (Landcare Research 2018) and LCDB4 (Landcare Research 2014) and geospatial databases.

Lake	Exotic Forest (% change)	High-producing exotic grassland (% change)	Low-producing exotic grassland (% change)	Short-rotation cropland (% change)
Camp	1.4 (0)	0 (0)	72.6 (0)	0 (0)
Clearwater	0.1 (0)	0 (0)	26.8 (0)	0 (0)
Denny	0 (0)	32.1(0)	3.7 (0)	0 (0)
Emily	0 (0)	0 (0)	79.2 (0)	0 (0)
Emma	0.3 (0)	0.1 (0)	38.0 (0)	0 (0)
Grasmere	0.1 (-0.2)	6.5 (0)	33.0 (+0.2)	0 (0)
Hawdon	0 (0)	0 (0)	48.1 (0)	0 (0)
Heron	0.2 (0)	8.5 (+0.6)	20.7 (-0.6)	0 (0)
Lyndon	0 (0)	0 (0)	33.8 (0)	0 (0)
Maori-front	0.4 (0)	44.9 (0)	30.0 (+0.02)	0.2 (0)
Maori-back	0 (0)	0 (0)	2.0 (0)	0 (0)
Pearson	0 (0)	5.3 (0)	25.6 (0)	0 (0)
Sarah	0 (0)	0.01 (0)	60.9 (0)	0 (0)

2.2. Calculating nutrient loads to lakes

The latest version of CLUES (V10.6) was used to recalculate total annual loads of TN and TP for 13 lakes originally included in the 2014 study (Kelly et al. 2014). Annual loads (tonnes/annum) of total nitrogen (TN) and total phosphorus (TP) to the lakes were estimated using a nutrient transport model combined with the regionally-based hydrological regression model, CLUES version 10.6 (Woods et al. 2006). Total N and TP loadings generated by this model reflect the effects of various land uses such as production forestry, low-intensity grazing, high-intensity grazing, dairy farming, horticulture and urban development and take into account upstream retention by lakes and wetlands.

Catchment land use in the 13 lake catchments was compared between the Land Cover Database version 4 (LCDB v4.0—Landcare Research 2014) on which the present CLUES version 10.6 is based, and the latest land cover information in Land Cover Database version 5.0 (LCDB v5.0—Landcare Research 2018). This approach was to determine which lakes required updated CLUES land-use scenarios based on more recent land cover information. A simple rule was applied: lake catchments that had land cover of agriculture or forestry classes differing between LCDB v4.0 and LCDB v54.0 by greater than 2% of the total catchment area, had updated LCDB v4.0 land-use scenarios run. Because landcover information had changed only marginally from 2012 (< 0.6% in all cases), this was done using the default land cover for the CLUES model of LCDB4, as done in 2014. Loads for individual inflow tributaries were accumulated to calculate the total loads of TP and TN to the lake in tonnes per year. Flow weighting of tributaries was conducted using mean average flow estimates for each inflow reach using the CLUES hydroedge layer. From this flow weighted load data, average annual loads could be calculated both as mean annual inflow concentration as well as a total mean annual flow weighted inflow concentration for both TP and TN.

The CLUES model produced an overall estimate of TN and TP load in tonnes per annum for each lake by summing the TN and TP loads for the tributary inflows. Mean annual inflow TN and TP concentrations were calculated by dividing tributary inflows by the mean annual flow obtained from the CLUES model hydro-edge function. From this flow-weighted load data, average annual loads could be calculated both as mean annual inflow concentration as well as a total mean annual flow-weighted inflow concentration for both TP and TN.

2.2.1. Waterbird contributions to annual nutrient loads

Waterbird contributions to annual nutrient loads were updated from Kelly et al. (2014) calculations, which were based on seasonal (4x per year) monitoring of waterbird abundances at 9 Ashburton Basin lakes over a 3-year period between 2009 and 2012 (Lakes Camp, Clearwater, Denny, Maori-front, Emily, Emma, Heron, Maori-back and

Roundabout). The most abundant species observed in the data set were the New Zealand scaup, Canada goose, black swan, mallard, coot and paradise shelduck. Bird numbers varied across seasons and from year to year.

For this study, the average seasonal abundances of waterbirds across each lake was transformed based on trends in annual winter bird count data that have been collected using a consistent methodology since 1984. This was done because waterbird numbers have been observed to be significantly declining over the period between this study (2016–2019) and the previous detailed seasonal monitoring conducted between 2009–2012 (Figure 6).

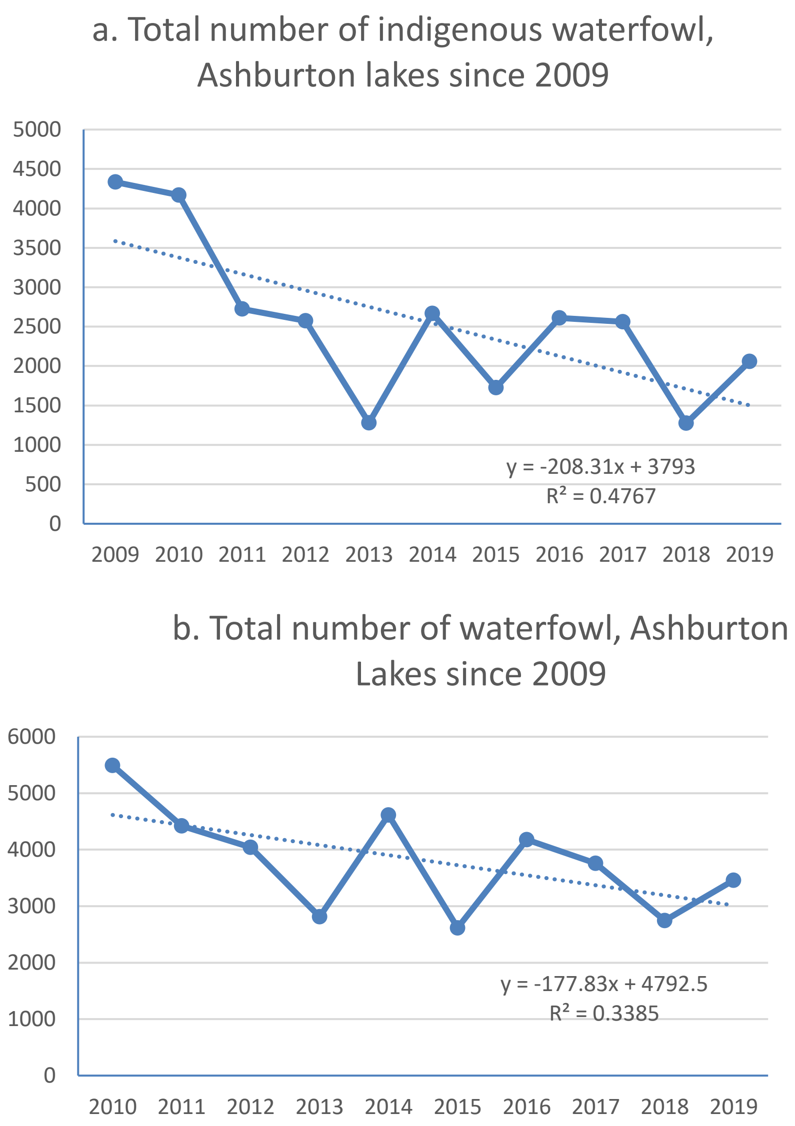


Figure 6. Total numbers of (a) indigenous waterfowl and (b) total waterfowl counted in nine Ashburton basin lakes between 2009 and 2019 during annual winter bird counts. Unpublished data provided by Department of Conservation (Colin O'Donnell, personal communication).

Mean seasonal waterbird abundance data for each lake over the period of 2009–2012 were transformed using an abundance ratio for each species calculated from winter bird count average annual abundances between 2009–2012 and 2016–2019, shown in Table 2.

Table 2. Ratio of abundance change in waterbirds in annual winter bird counts at nine Ashburton Basin lakes between the period of 2009-2012 and 2016-2019. Values less than 1 indicate a decline in abundance whereas values greater than 1 indicate an increase in abundance.

Species	**Abundance ratio**
Black swan	1.023
Canada goose	0.686
Mallard	1.196
Duck spp.	2.000
Paradise shelduck	1.090
Grey duck	0.219
NZ shoveler	1.634
NZ scaup	0.580
Grey teal	1.350
Average	0.714

Based on previous studies of waterbirds for the Rotorua Lakes, Don and Donovan (2002) quantified nutrient loading from different species of waterbirds (Table 3). These calculations took into account the volume of excreta different bird species typically produce per day, the concentration of TN and TP in excreta and the proportion of time the birds spent on the lakes. To calculate total seasonal loads per species on each lake, we combined the mean seasonal average waterbird abundances and multiplied these by the daily nutrient loads per bird to estimate the mean daily TP and TN from waterbirds for each lake. Daily loads were then added for each season to calculate total annual TN and TP loads from waterfowl for each lake. For further detail on this methodology can be seen in Kelly et al. (2014).

Table 3. Contribution of different species of waterbirds to loading of total nitrogen (TN) and total phosphorus (TP). Derived from Don and Donovan (2002). na = not applied. Adj = adjusted.

Species	Proportion time bird spent on lake	TN load per bird g/day (adj)	TP load per bird g/day (adj)
Banded dotterel	0.2	0.04	0.18
Bittern	0.4	0.39	1.06
Black shag	0.5	0.45	1.94
Black swan	0.9	1.41	0.44
Black-backed gull	0.4	0.18	0.10
Black-billed gull	0.4	0.18	0.10
Black-fronted tern	0.4	0.18	0.10
Canada goose	0.7	1.10	0.34
Coot	0.9	0.25	0.08
Crested grebe	0.9	0.18	0.80
Duck spp.	0.7	1.10	0.34
Grey duck	0.5	0.79	0.25
Grey teal	0.5	0.79	0.25
Harrier	na	na	na
Hybrid / black stilt	0.4	0.08	0.36
Little shag	0.5	0.45	1.94
Mallard	0.5	0.79	0.25
NZ falcon	na	na	na
NZ pipit	na	na	na
NZ scaup	0.9	0.55	0.17
NZ shoveler	0.5	0.79	0.25
Paradise shelduck	0.5	0.79	0.25
Pied oyster-catcher	0.4	0.08	0.36
Pied stilt	0.4	0.08	0.36
Pukeko	0.5	0.79	0.25
Red-billed gull	na	na	na
Spur-winger plover	0.5	0.10	0.45
White heron	0.5	0.49	1.32
White-faced heron	0.5	0.49	1.32
White-fronted tern	0.4	0.39	1.06

2.3. Vollenweider modelling

To test and verify the accuracy of the predicted nutrient loadings from the CLUES model and their applicability to lakes in the Canterbury high-country region, the model predictions were correlated against lake water quality conditions in 27 lakes for which water quality data were available as part of the previous study in 2014 (Kelly et al. 2014).

Vollenweider models were used to transform the predicted inflow nutrient loading rates (from CLUES) into in-lake TN and TP concentrations. Vollenweider (1982) found that annual average TP and TN concentrations in lakes (TP_{Lake} and TN_{Lake} in mg/m^3) could be estimated from lake flushing rates and inflow concentrations. Two sets of Vollenweider equations optimised for Canterbury high-country shallow lakes and deep lakes (Kelly et al. 2014) were used for the transformation of loads to in-lake concentrations according to equations 1 to 4. In addition to these 2014 study models, a recent national study calculated Vollenweider regression models for 76 (TN model) and 84 (TP model) monitored lakes in New Zealand (Abell et al. 2019), which were tested against the original 27 lake study data as well as the updated 13 lake CLUES 10.6 load (equations 5 to 7):

Shallow lakes (from Kelly et al. 2014):

$$\mathrm{TP_{Lake}} = 3.019\left[\mathrm{TP_{Inflow}}/\left(1+\sqrt{\tau}\right)\right]^{0.638} \quad (1)$$

$$\mathrm{TN_{Lake}} = 33.021\left[\mathrm{TN_{Inflow}}/\left(1+\sqrt{\tau}\right)\right]^{0.390} \quad (2)$$

Deep lakes (from Kelly et al. 2014):

$$\mathrm{TP_{Lake}} = 5.304\left[\mathrm{TP_{Inflow}}/\left(1+\sqrt{\tau}\right)\right]^{0.276} \quad (3)$$

$$\mathrm{TN_{Lake}} = 65.042\left[\mathrm{TN_{Inflow}}/\left(1+\sqrt{\tau}\right)\right]^{0.305} \quad (4)$$

Shallow and deep lakes (from Abell et al. 2019)

$$\text{Shallow } \mathrm{TP_{Lake}} = [Log10\ \mathrm{TP_{Inflow}}/(1.44\tau)^{0.13}] \quad (5)$$

$$\text{Deep } \mathrm{TP_{Lake}} = [Log10\ \mathrm{TP_{Inflow}}/(\tau)^{0.13}] \quad (6)$$

$$\mathrm{TN_{Lake}} = 33.398\left[\mathrm{TN_{Inflow}}^{0.54}/(\mathrm{Zmax})^{0.41}\right] \quad (7)$$

where TP_{Inflow} and TN_{Inflow} are the annual average inflow concentrations of P and N, respectively (mg m^{-3}), and τ is the hydraulic retention time of the lake.

TP_{inflow} and TN_{inflow} were derived from the flow-weighted average nutrient concentrations derived from the CLUES catchment model (see above) and to calculate an annual mean discharge to the lake. The multiplier (a) and exponent (b) terms for the functions were optimised for the 13 Canterbury high-country lakes in a non-linear regression model in the statistical program ‘R’ (Version 3.4.1) using the measured values of TN_{Lake} and TP_{Lake} from monitoring data (median of the annual averages for the years 2015 to 2020).

Parameters used in calibrating Vollenweider models, including lake volume, hydraulic residence time (τ), mean depth (Z_{max}), and fetch were obtained from the FENZ geo-database (Leathwick et al*.* 2010), and were modified where more accurate data (usually depth and volume) were available.

2.4. Lake ecological integrity response variables

Physico-chemical data for the lakes were obtained from Environment Canterbury State of the Environment monitoring of 13 Canterbury high-country lakes between 2015 and 2020. This included mean annual concentrations of TP, TN, chl-*a*, and turbidity measured between December to April (i.e*.* 5 months over spring–summer annually).

Water clarity measurements, such as Secchi disk depth or the diffuse light attenuation coefficient were not available for the lakes, due to the lakes being routinely monitored by helicopter. Turbidity measurements were taken and considered in the analysis as a surrogate for Secchi, but they cannot readily be used to determine a clarity index (Bayer & Meredith 2020).

Linear regression analyses were used to relate water quality variables with Vollenweider transformed TN and TP loads for the lake set. A small number of outlier lakes were identified in the data set in some regression functions, and accordingly were omitted from regression models. The reason for omitting outliers is discussed in this report. All analyses were conducted using Systat version 10 statistical software (SPSS Inc, Chicago, USA). Regression slopes, significance (P-values) and coefficients of determination (r-squared values) are reported for all significant regressions (i.e., $P < 0.05$, $R^2 > 0.3$).

3. RESULTS AND DISCUSSION

3.1. Stream inflows

CLUES (V10.6) predicted mean annual inflow TN and TP concentrations compared against river inflow water quality monitoring data (Ashburton Basin only) for 14 river monitoring sites between 2015–2020 suggest only moderate correlation between measured and modelled data (Figure 7). There was a poor correlation between mean annual TN predicted by the CLUES model compared with mean measured data (Figure 7b: P = 0.331, r^2 = 0.12). This was likely affected by the short length of monitoring records for some sites (e.g., Lake Clearwater and Heron sites). Similarly, for TP the relationship between monitored mean TP concentration and mean annual TP predicted by CLUES for the 14 sites was not significant (Figure 7a: P = 0.367, r^2 = 0.11). Predictions between measured and modelled concentrations were generally better for the Maori Lakes and Clearwater sites than for Lake Heron, which overpredicted TP in inflows. The short monitoring record for Lake Heron, which did not include any high flow monitoring events, is likely to have contributed to the poor correlations. Other 'reference' sites from the Ashburton basin including Paddle Hill stream were also greatly overpredicted by CLUES relative to long-term measured mean concentrations of TN and TP.

Measured TN and TP inflow concentrations were consistently lower than predicted annual average values by CLUES for all sites. This would be expected because annual mean CLUES models would also include high nutrient loads during flood-flows. Direct comparison to spot measurements would require more detailed flood-stage modelling to determine annual loads because of the hydrologic complexity. Therefore, it is expected that CLUES estimates should exceed measured TN and TP values, and this was the case for 3 of the 4 tributary sites. However, the particularly high values for TP predicted by CLUES for the Lake Heron tributaries requires further scrutiny and suggests some uncertainty around loads from these tributaries. Similarly, the relatively high values of TN and TP predicted by CLUES for the reference site at Paddle Hill Stream suggests some caution around inferring nutrient loads from undeveloped catchment areas in the conservation estate, as reported in previous studies of tussock grassland in the Lake Clearwater catchment (Wadworth-Watts et al. 2013).

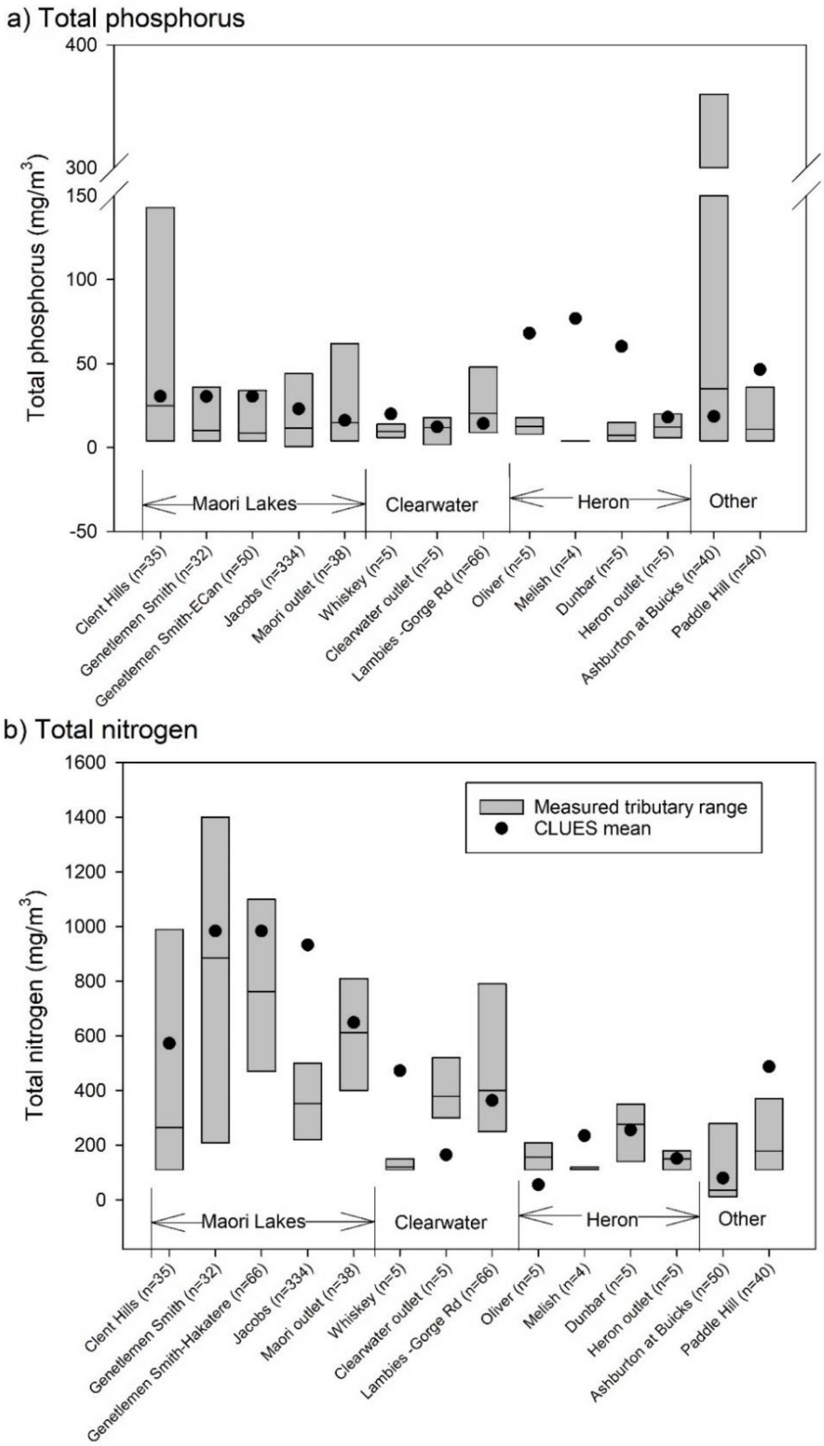


Figure 7. Mean and data range (grey bars) between 2015 and 2020 for a) total phosphorus and b) total nitrogen in tributary inflows to three Ashburton Basin lakes, as well as mean annual concentrations (black circles) predicted by CLUES nutrient load model (version 10.6) for the 14 Ashburton basin river sites.

3.2. Waterbird nutrient contributions

Updated calculations of waterbird contributions to Ashburton basin lake nutrient loads, taking into account bird population trends between 2010 and 2019, suggest that waterbird contributions to total annual nutrient loads are relatively small for TN (< 5% total annual load), but can be quite significant for TP (up to 32.5% of annual TP load) (Table 4). Higher contributions to annual TP loads by waterbirds occurred mainly where bird densities were high and lakes were relatively small with small catchment areas, such as Lakes Emily and Camp.

Lake Heron had the highest nutrient loading from waterbirds (TN = 0.359 t/y; TP = 0.132 t/y) while Lake Camp the lowest nutrient loading (TN = 0.015 t/y; TP = 0.009 t/y). However, on a per hectare basis, Lake Denny experienced the greatest nutrient load from waterbirds, followed by the Maori Lakes and Lake Emily, as these smaller lakes had much higher waterbird densities. The trend for declining waterbird populations in Ashburton Basin between 2010 and 2019 had a minor affect on the overall predictions of waterbird contributions to annual nutrient loads. Average proportional waterbird contributions TP loads increased from being on average 9.3% in 2011–2013 to 9.5% in 2017–2019. The proportional contribution of waterbirds to annual TN loads declined from on averge 2.6% in 2011–2013 to 1.4% in 2016–2019. This proportional decline in bird TN load was mostly related to predicted increases in catchment TN load.

Table 4. Estimates of total nitrogen (TN) and total phosphorus (TP) loads by catchment and waterbird sources in eight Ashburton Basin lakes.

Lake	Lake area (ha)	Catchment area (ha)	Waterbird TN load (t/y)	Waterbird TP load (t/y)	Waterbird TN load (kg/ha/y)	Waterbird TP load (kg/ha/y)	Waterbird TN contribution (% total load)	Waterbird TP contribution (% total load)
Camp	44	606	0.015	0.009	0.34	0.21	0.3	4.9
Clearwater	197	4,172	0.084	0.035	0.42	0.18	0.6	1.9
Denny	5	1,867	0.101	0.033	18.64	6.19	1.4	8.1
Emily	19	241	0.062	0.026	3.22	1.35	5.0	32.5
Emma	167	3,560	0.149	0.061	0.89	0.36	2.2	20.5
Heron	692	11,094	0.359	0.132	0.52	0.19	1.2	1.4
Maori front	10	8,355	0.039	0.013	4.10	1.34	0.1	0.6
Maori back	10	5,200	0.042	0.015	4.41	1.53	0.6	6.4

3.3. Updated Vollenweider modelling

3.3.1. Total nitrogen Vollenweider models

There were reasonable predictions of total annual TN loads to 13 lakes calculated using CLUES 10.6 using the 2014 nutrient retention model when compared with in-lake nutrient concentrations (Figure 8; Kelly et al. 2014). For the TN CLUES model predictions, 8 lakes fit reasonably well to the Kelly et al. (2014) TN retention model (with differing functions for shallow versus deep lakes). Five lakes were poorly aligned with the model fit. Measured in-lake TN concentrations (2015–2020 5-year median) in Lakes Emma, Clearwater, Maori-front and Denny were all considerably underpredicted by the Vollenweider transformed CLUES model loads (Figure 8a). However, Lakes Emma and Clearwater were similarly underpredicted by CLUES loads in 2014 and were omitted from the regression model due to being considered outliers as the error was assumed to be in the catchment input component. Underprediction of in-lake TN by catchment load models were thought to be related to groundwater (Wadworth-Watts et al. 2013) or internal nutrient cycling processes not accounted for in the catchment model. In the 2014 study, water quality data for Lake Denny were also adjusted to omit one year of very high nutrient concentrations where the lake had excessive phytoplankton blooms. These very high nutrient concentrations have more recently returned to Lake Denny, and the CLUES catchment model greatly underpredicted measured in-lake TN values. Lake Heron was the only lake in the data set for which the CLUES 10.6 model appears to be significantly over-predicting in lake nutrient status. It is uncertain why this has occurred, as 2014 CLUES model predictions were more in line with in-lake values. Lake Hawdon was also more closely predicted by CLUES model predictions in the previous 2014 version (V10.1) than in the latest version and it is uncertain why this has changed. Closer scrutiny of CLUES 10.6 load predictions for specific tributaries is required to evaluate if any unrealistic model prediction values that are driving these changes.

A repeated measures analysis of variance was conducted to test for differences in the data distributions for both the Vollenweider predicted nutrient in-lake concentration and measured 5-year median between years (i.e., 2014 and 2020). For TN load models, there was no significant effect of year ($F = 1.402$, $P = 0.244$), but there was a significant difference between deep and shallow lakes in terms of their predicted loads ($F = 27.189$, $P < 0.0001$). This indicated that there is no statistical reason behind using 2020 data in the regression relationship derived in 2014, but does indicate the importance of using different models between deep and shallow lakes. This supports the use of the Vollenweider optimised model (from Kelly et al. 2014) that derived nutrient retention functions independently for deep and shallow lakes.

The use of an equation from a more recently developed TN retention model for a national study of New Zealand lakes (Abell et al. 2019) did not yield improved model predictions of in-lake nutrient TN concentration at a regional scale (Figure 8b). Most notably the slope of the predicted modelled:measured line was much further from a 1:1 relationship suggesting poorer predictive power. This pattern was prevalent for both the 2014 and 2021 CLUES TN load model predictions. As such, we suggest that the regionally calibrated model is likely to provide the best fit to in-lake water quality for the Canterbury high-country lake set.

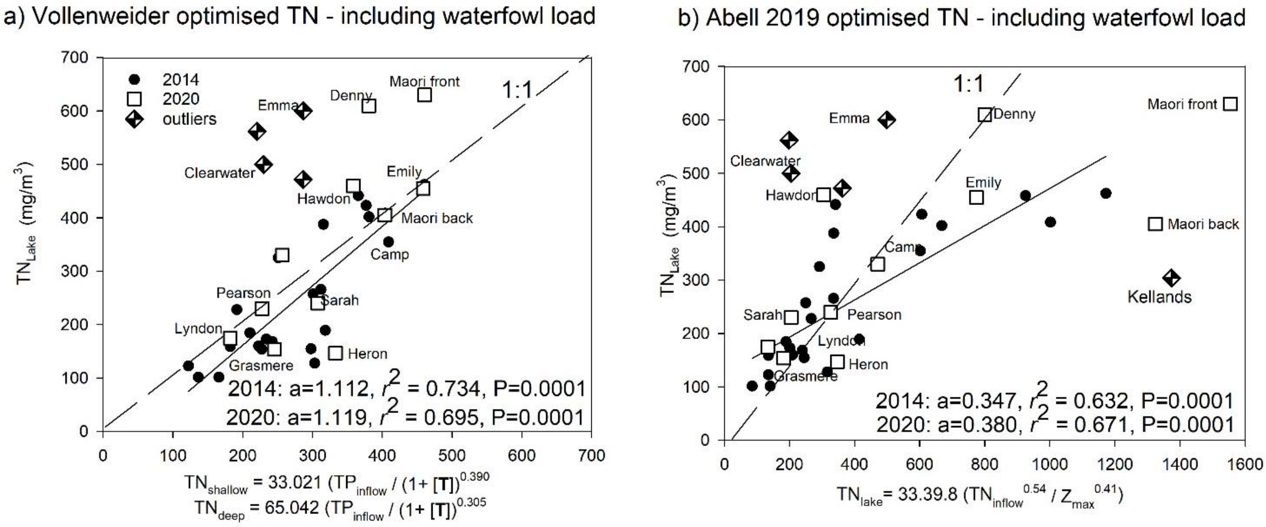


Figure 8. Relationships between in-lake total nitrogen (TN) concentrations and two Vollenweider model predicted TN concentrations based on combined CLUES model inflow concentrations and waterbird loads for 27 Canterbury high-country lakes. CLUES models were for Version 10.1 (2014, black circles) and V10.6 (2020, hollow squares), and Vollenweider models were from a) Kelly et al. (2014) and b) Abell et al. (2019). Note that Lakes Emma, Clearwater, and Kellands Pond were omitted from the regression models in both years as outliers, as denoted by diamond symbols.

3.3.2. Total phosphorus Vollenweider models

Updated CLUES 10.6 model predictions of TP loads for Canterbury lakes fit reasonably well to the Kelly et al. (2014) TP retention model for 9 lakes, whereas 4 lakes were poorly aligned with the model fit. Measured in-lake TP concentrations (5-year median 2015–2020) in Lakes Emma and Denny were considerably underpredicted by the Vollenweider-transformed CLUES loads, whereas they were highly overpredicted for Maori-front Lake and Lake Hawdon (Figure 9a). It is notable that Lakes Emma and Denny were excluded from the fitted TP retention model in the 2014 study due to the lakes being considered outliers (Kelly et al. 2014), and this pattern still exists for the 2020 updated CLUES predictions. We suggest that the CLUES catchment model is unlikely to be sufficient for predicting in-lake concentrations for these 2 lakes, possibly related to internal nutrient cycling as often occurs for high-nutrient status lakes (Søndergaard et al. 1993).

Overall, the CLUES 10.6 model slightly overpredicts in-lake TP concentrations for a larger number of lakes than in 2014, being most pronounced for Lakes Hawdon and Maori front Lake, indicated by the number of points in the 2020 dataset that fitted below the regression line for the Vollenweider function. However, a repeated measures analysis of variance conducted to test for differences in the data distributions between years indicated there was no significant effect of year (F = 139.6, P = 0.065) on CLUES-predicted TP loads. Similar to findings for TN, there were significant differences in TP data distributions between deep and shallow lakes (F = 582, P < 0.001). This finding is clearly supported by our understanding of TP recycling processes that differ between shallow and deep lakes, with sediment resuspension and stratification greatly differing between deep and shallow systems (Scheffer et al. 1993).

The use of a more recently developed TP retention model from a national study of New Zealand lakes did not yield improved model predictions of in-lake nutrient TP concentration at a regional scale (Abell et al. 2019), although TP model prediction were more closely aligned than for TN. We would still suggest the regionally calibrated model is likely to provide the best fit to water quality for the Canterbury lake set.

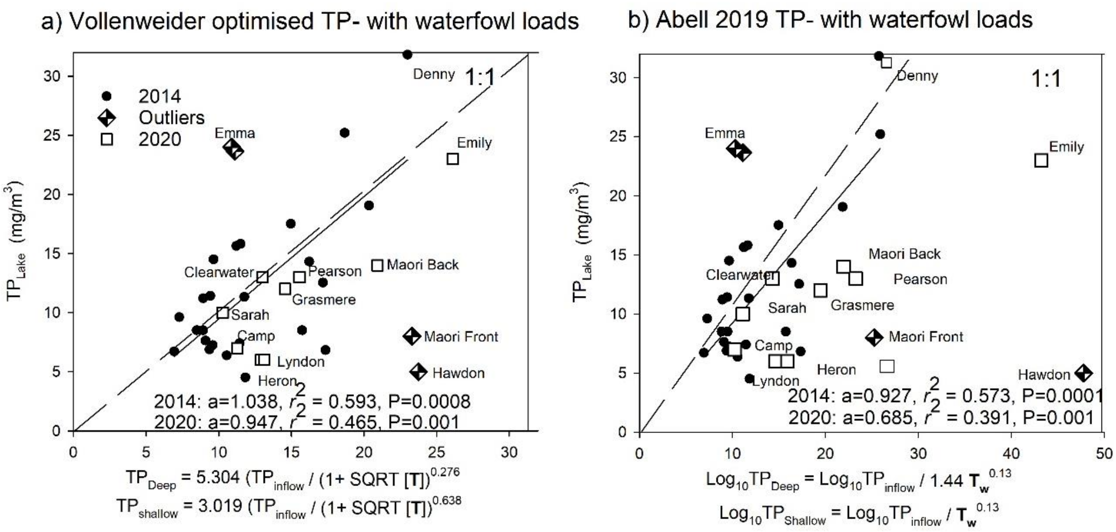


Figure 9. Relationships between in-lake total phosphorus (TP) concentrations and two Vollenweider model predicted TN concentrations based on combined CLUES model inflow concentrations and waterbird loads for 27 Canterbury high-country lakes. CLUES models were for Version 10.1 (2014) and V10.6 (2020), and Vollenweider models were from (a) Kelly et al. (2014) and (b) Abell et al. (2019). Note that Lakes Emma, Denny, Maori-front and Hawdon were omitted from the regression models as outliers, as denoted by diamond symbols.

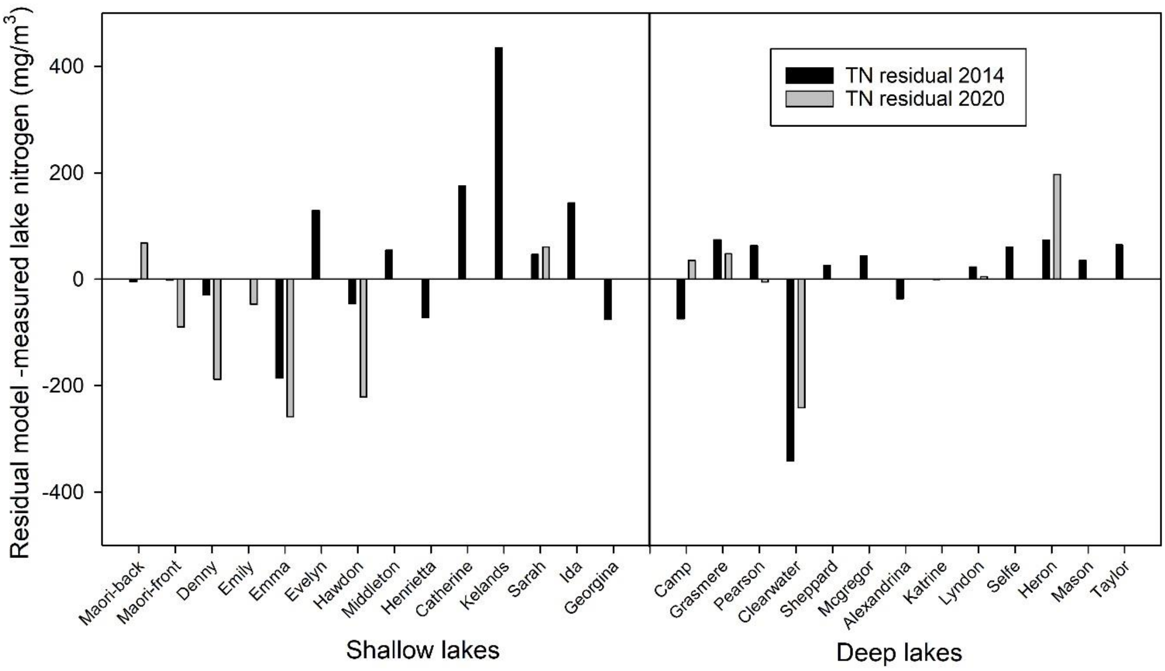
3.4. Analyses of in-lake catchment load differences

The use of the more recent version of CLUES (V10.6) in predicting TN in-lake concentrations appears to be relatively robust to its application in the Vollenweider function derived for 27 lakes in 2014. Four lakes (Emma, Denny, Hawdon, Clearwater) had high residuals of modelled to measured concentrations of in-lake TN (Figure 10a), but several of these lakes were previously observed to have high residuals (Kelly et al. 2014), and therefore have been consistent between 2014 and 2020 studies. High residuals of modelled/measured in lake nutrients for Lakes Emma and Clearwater using CLUES in both 2014 and 2020 studies suggests the CLUES catchment modelling approach may be poorly suited to setting load targets for these lakes, unless other factors are included (e.g., internal recycling, groundwater inflows). This has been previously discussed in Kelly et al. (2014).

There was evidence of a greater number of underpredictions of in-lake TN by catchment loads with Version 10.6, particularly for shallow lakes, as evidenced by lower than predicted in-lake concentrations (e.g., Emma, Denny, Hawdon, Clearwater). This may be related to unaccounted for N loads contained in groundwater, N-fixation by cyanobacteria, or possibly from in-lake recycling. This suggests that there remain some inaccuracies around CLUES predictions of TN, particularly in shallow lakes. Poorer performance of the Vollenweider model for predicting in-lake TN for shallow lakes also suggests the 2014 model may be less accurate for shallow lakes. Lake Heron was the only lake to have been significantly over-predicted for in-lake TN, consistent with the pattern for low TN and TP observed for tributary stream monitoring sites draining the conservation estate land in other monitored reference streams (e.g., Paddle Hill Stream, Whiskey Creek).

The use of CLUES 10.6 for modelling in-lake TP concentrations resulted in good in-lake TP predictions for deep lakes in the data set, but shallow lakes had consistently higher residuals of modelled to measured, in-lake TP concentrations (Figure 10b). The tendency for CLUES 10.6 to overpredict in-lake TP for a larger number of lakes in 2020 (Hawdon, Maori-front), suggests potentially that the version change may have affected overall load predictions, or that the 2014 Vollenweider model is poorly parametrised for the 2020 load data, particularly for shallow lakes. Alternatively, the catchment model greatly underpredicted in-lake TP concentration for Lake Emma and Denny, which may have been related to other in-lake factors not accounted for by CLUES. As such we suggest that the catchment model approach, in isolation, is poorly suited to understanding nutrient dynamics in Lakes Denny and Emma, where contributions from internal nutrient cycling need to be investigated further to understand drivers of in-lake nutrient conditions. Other unaccounted for and site-specific nutrient sources could also contribute to this error (e.g., in-stream works, stock in waterways, excessive fertiliser application, leaking septic tanks, etc.) and would have to be considered on a lake by lake basis.

a) Total nitrogen



b) Total phosphorus

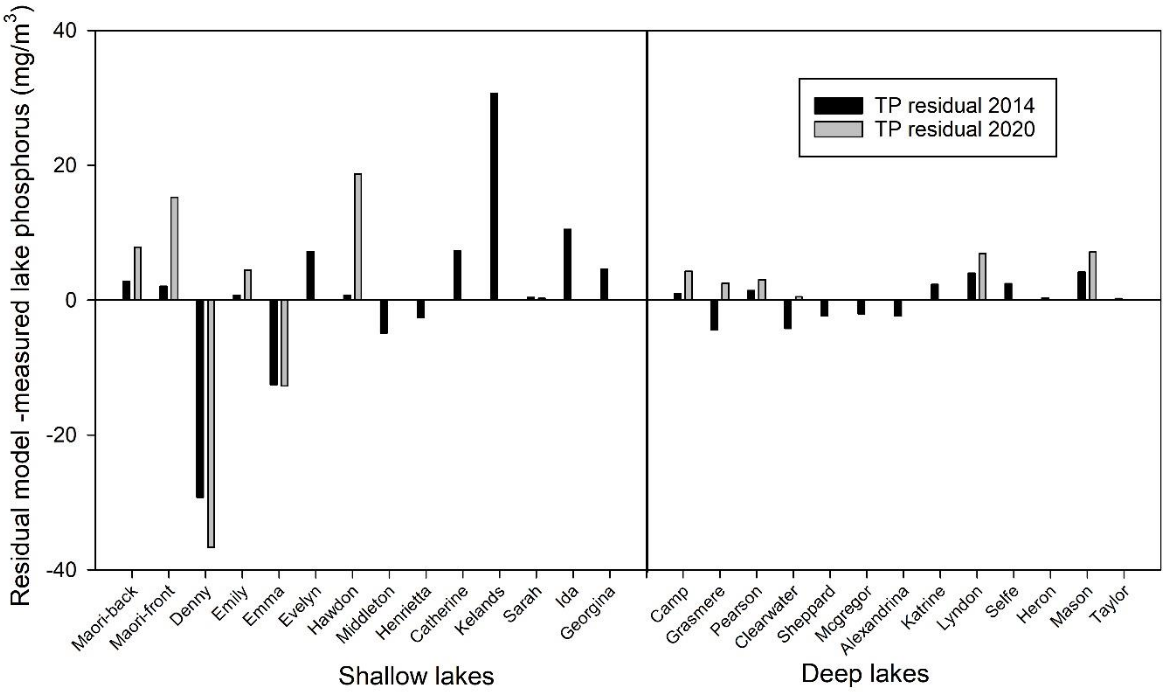


Figure 10. Residuals of modelled to measured data for CLUES model predictions of in-lake a) total nitrogen, and b) total phosphorus for 27 Canterbury high-country lakes. Data shown are for modelled predictions in 2014 using CLUES V10.1 (black bars) and in 2020 using Clues 10.6 (grey bars). Note that only 13 of the 27 lakes were modelled in 2020.

3.5. Loading to meet in-lake benchmarks

Estimates of changes in catchment nutrient loads required to meet in-lake nutrient and chl-*a* objectives were calculated based on reducing in-lake TN and TP from their most recent 5-year mean (2015–2020) to the target levels, where necessary (Table 5). The Environment Canterbury Land and Water plan objective for all lakes in the nutrient sensitive zones is TLI 3 and chl-*a* is 2 mg/m^3, with exception of the Maori lakes and Lake Emily where the plan objective is a TLI of 4 and chl-*a* of 5 mg/m^3. Therefore, TN and TP loads and concentration reductions were calculated based on the TN and TP concentrations corresponding to plan objectives of TLI of 3 (160 mg TN/m^3 and 9 mg TP/m^3) and TLI 4 (340 mg TN/m^3 and 20 mg TP/m^3), respectively. Necessary load reductions to meet benchmarks were calculated using the previously derived Vollenweider models for lakes that had a good model fit for the 2020 CLUES 10.6 predictions, with lakes having poor model fits omitted from the calculations. Calculations of nutrient loading to meet chl-*a* benchmarks was also considered by calculating the equivalent in-lake TP concentration necessary to meet the in-lake chl-*a* through a linear regression of TP to chl-*a* across all the lakes (27 lake set combined data for 2014 and 2020; $r^2 = 0.74$, $P = 0.001$; Appendix 1). It should be noted that the estimated of load reductions required to meet plan limits should be considered as indicative due to the expected uncertainty in predicting responses of lakes to future load changes. Therefore, only ranges in load reductions based on small (< 33%), moderate (34–66%) and large (> 66%) are cited. Uncertainty in model predictions is further discussed in Section 4 of this report.

3.5.1. Load predictions to meet TN standards

Based on 5-year average monitoring data (2015-2020) of in-lake TN concentrations, 4 of 13 lakes require large (> 66%) reductions in TN to meet plan objectives, 5 require moderate reductions (34–66%), and 3 required small reductions (< 33%) to meet the objectives, while Lake Grasmere meets its objectives (Table 5). The associated predictions in the required reductions in catchment N loads necessary to meet the plan TN objectives indicated that large reductions were required for 6 of the 9 lakes considered (Lakes Camp, Emily, Maori-back, Maori-front, Hawdon and Sarah), a moderate reduction (34-66%) was required for Lake Pearson, and small (< 33%) reductions were required for Lakes Heron and Lyndon. No reduction was required to meet the in-lake TN objective for Lake Grasmere. For Lake Emily, the large requirement for catchment N load reduction relative to the small reduction of in-lake TN concentration was mostly attributed to the larger contribution by waterbirds to total lake N load. Calculations of load reductions are based only on the reducing catchment load portion of the total load did not consider reduction in direct loads from waterbirds. As a result the proportional reduction in catchment nutrient load tends to be greater than the proportional change in nutrient concentration.

Three lakes (Lakes Clearwater, Emma, Denny) were omitted from conducting load reduction calculations because of their poorer fit to the Vollenweider mass balance model. It is anticipated that other nutrient sources not accounted for in our modelling such as groundwater inputs, internal recycling, and N-fixation by cyanobacteria could contribute significantly to their relatively high in-lake TN, so confidently predicting catchment load reductions was too uncertain. However, it is anticipated that at least moderate reductions in catchment N load would be required for these 4 lakes to meet the plan standards given their high in-lake nutrient status.

3.5.2. Load predictions to meet TP standards

Based on 5-year average monitoring data of in-lake TP concentrations, Lakes Denny and Emma required large (> 66%) reductions in TP to meet plan objectives, Lakes Clearwater and Grasmere required moderate reduction (34–66%), and 3 lakes (Emily, Pearson and Sarah) required small reductions (< 33%) (Table 5). Six of 13 lakes met the plan TP objectives, which was a greater number than for TN. Associated predictions in the required reductions in catchment P loads to meet the in-lake TP plan objectives indicated that large (> 66%) reductions were required for Lakes Clearwater and Pearson, moderate reductions (34-66%) were required for Lakes Emily and Grasmere, and a small (< 33%) reduction was required for Lake Sarah. No reduction was required to meet TP plan objectives for Lakes Camp, Heron, Maori-front, Maori-back, Hawdon and Lyndon based on the 2015–2020 mean concentration.

Lakes Emma and Denny were omitted from calculations of P load reductions to meet plan objectives due to other factors, thought to significantly affect their high in-lake TP status, not accounted for in the catchment modelling process. This could include in-lake P recycling from lake sediments, wind-driven resuspension of lake sediments, or possibly losses from immediate surrounding wetlands. Both lakes had high in-lake nutrient status that poorly related to predicted loads from CLUES and waterbirds. However, given their high in-lake TP concentrations it is probable that significant catchment load reductions could be required to meet the relative plan TP objective of 160 mg TP/m^3.

3.5.3. Load predictions to meet chlorophyll-a standards

Based on 5-year average monitoring data of in-lake chl-*a* concentrations, 4 lakes required large (> 66%) reductions in chl-*a* to meet plan objectives, 5 required moderate reductions (34–66%), and 4 required small reductions (< 33%) (Table 5). None of the 13 lakes considered met their plan objectives for chl-*a* based on 2015–2020 mean chl-*a* concentration. The associated predictions in the required reductions in catchment nutrient loads to meet the plan in-lake chl-*a* objectives indicated that large (> 66%) reductions were required for 6 lakes (Lakes Camp, Clearwater, Emily, Maori-front, Grasmere and Pearson), moderate reductions (34–66%) in nutrient load were required for Lakes Lyndon and Maori-back Lake, and a small (< 33%) reduction in P load was required for Lakes Sarah and Hawdon.

Lakes Emma and Denny were omitted from these load reduction calculations because, as discussed previously, it is likely that other in-lake factors are significantly contributing to nutrient dynamics. However, it is worth noting that Lakes Emma and Denny would also likely require catchment load reductions as well as other in-lake management measures to control internal loading to meet this limit. Lake Heron was also omitted from load reduction calculations because of the atypically high in-lake chl-*a* to TP concentrations observed, suggestive that factors other than TN and TP loads are likely to be driving chl-*a* dynamics in the lake. Although it is uncertain what is driving this trend, possibly dissolved nutrient sources were more prevalent in the lake that contributed more directly to phytoplankton biomass relative to total nutrient concentrations. Investigation of the phytoplankton species composition could also yield insights into phytoplankton dynamics and possible nutrient fixation or trace metal enrichment.

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Table 5. CLUES predicted total nitrogen and total phosphorus loads to Canterbury high-country lakes and the associated nutrient concentration and estimated load reductions to meet to meet the Environment Canterbury Laned and Water Plan objectives. Note that chlorophyll-*a* (chl-*a*) predictions are based on changes in total phosphorus according to the linear regression function (Appendix 1). Green boxes indicate the parameter meets the plan objective, blue require small reductions (< 33%), orange require moderate reductions (34–66%), and red boxes require large reductions (67–99%).

Lake	CLUES TN Catchment Load (T/y)	CLUES TP Catchment Load (T/y)	TN mean 2015-2020 (mg/m³)	TP mean 2015-2020 (mg/m³)	Chl-*a* mean 2015-2020 (mg/m³)	TN reduction to meet plan target* (%)	TP reduction to meet plan target*(%)	Chl-*a* reduction to meet chl-*a* plan target*(%)	TN Load reduction to meet TN plan target*	TP Load reduction to meet TP plan target *	Nutrient Load reduction to meet chl-*a* plan target *
Ashburton basin lakes											
Camp	5.18	0.18	334	7.4	2.9	52	meets	32	large	meets	large
Clearwater	12.01	1.83	510	16.6	4.6	69	46	56	n/a	large	large
Denny	6.99	0.38	965	125.5	20.8	83	93	90	n/a	n/a	n/a
Emily	1.17	0.05	488	29.2	9.0	30	31	45	large	moderate	large
Emma	6.46	0.23	628	27.0	11.1	75	67	82	n/a	n/a	n/a
Heron	30.04	9.28	167	7.9	7.5	4	meets	73	small	meets	n/a
Maori-front	58.26	1.96	506	19.4	12.0	48	meets	51	large	meets	large
Maori-back	7.52	0.21	648	15.1	10.1	34	meets	58	large	meets	moderate
Waimakiriri Lakes											
Grasmere	3.01	1.90	154	14.7	3.9	meets	39	48	meets	moderate	large
Hawdon	0.13	0.06	619	7.3	2.7	74	meets	26	large	meets	small
Lyndon	3.54	1.81	172	3.1	2.5	7	meets	20	small	meets	moderate
Pearson	10.65	4.89	244	13.0	5.5	35	31	64	moderate	large	large
Sarah	1.26	0.17	258	10.8	2.5	38	17	19	large	small	small

*Note that for the Environment Canterbury Land and Water plan objective for all lakes in the nutrient sensitive zones TLI is 3 and objective for chlorophyll-*a* is 2 mg/m³, with exception of the Maori Lakes and Lake Emily, where the plan objective is a TLI of 4 and chlorophyll-*a* of 5 mg/m³. TN and TP load and concentration reductions were calculated based on the TN and TP concentrations corresponding to plan objectives of TLI of 3 (160 mg TN/m³ and 9 mg TP/m³) and TLI 4 (340 mg TN/m³ and 20 mg TP/m³), respectively. Due to poor Vollenweider model fit Lakes Emma and Denny were omitted from TN and TP and chl-*a* load reduction calculations, and Lakes Clearwater and Maori-front were omitted from TN load reduction calculations, shown as 'n/a' in data field. Lake Heron was omitted from chl-*a* calculations due to atypical nutrient chl-*a* ratios.

4. CONCLUSIONS AND RECOMMENDATIONS

The updating of nutrient load predictions for a subset of 13 Ashburton and Waimakiriri lakes using CLUES 10.6 appears to provide predictions of nutrient loads to these high-country lakes that are reasonably consistent to recent modelling work conducted in 2014. Overall, the newer version of CLUES 10.6 was more likely to predict higher nutrient loads to lakes than the previous version (10.2) used in the 2014 study, particularly for shallow lakes. Reasons for this were not fully understood as there were no significant changes in catchment landcover between the two study periods. Catchment model predictions of ‘expected’ in-lake nutrient status for some lakes that were previously thought to be poorly aligned with measured in-lake monitoring values (from monitoring) were mostly consistent between study years. This affected a smaller subset of lakes (mainly Lakes Emma, Denny, Hawdon and Clearwater). For these lakes, further investigation into factors that are driving nutrient dynamics are required, and could consist of in-lake processing, groundwater contributions, or other unknown factors.

4.1. CLUES V10.6 TN model predictions

Updated calculations of TN loads for 13 of the high-country lakes using CLUES 10.6 appear to provide a reasonable comparative method for assessing in-lake TN concentrations as in the 2014 study. For shallow lakes in particular, the newer load predictions resulted in slightly higher residuals of modelled to measured values (Lakes Hawdon, Emma and Denny) than in 2014, and these should be looked into in greater detail, possibly related to groundwater or internal nutrient cycling. It was beyond the scope of this study to update the Vollenweider function for shallow lakes from Kelly et al. (2014), and therefore it is recommended the previous model is used for deep lakes, with consideration of updating the Vollenweider function for shallow lakes which is also recommended for the TP loads (discussed below) and could be done simultaneously.

For a small number of lakes (Emma, Denny, Clearwater) we suggest that catchment load calculations are unlikely to be sufficient on their own to predict in-lake TN concentrations as other processes appear to be driving large differences between modelled and measured values. For these lakes, follow-up studies would need to be conducted around quantifying internal nutrient cycling, N-fixation by bloom-forming cyanobacteria, and potentially groundwater inputs to get a more robust understanding of how catchment management will affect in-lake TN concentrations.

4.2. CLUES V10.6 TP model predictions

Updated calculations of TP loads using CLUES 10.6 for 13 of the high-country lakes appears to have provided reasonably comparable predictions as in 2014 of in-lake TP for deep lakes, but tended to overpredict in-lake TP concentration for a number of shallow lakes. It was beyond the scope of this project to update the Vollenweider retention model for all 27 of the original Canterbury high-country lake dataset. Therefore, there remains some uncertainty around some of the shallow lake TP predictions.

Greater variability in TP concentrations in shallow lakes associated with wind resuspension and nutrient recycling generally means that TP is harder to accurately model in shallow lakes lacking extensive macrophyte cover (Scheffer et al. 1993). This is because of the greater range of in-lake processes that drive water column TP and their greater sensitivity to wind are not considered in the model. It is apparent that some of the lakes (Lakes Emma and Denny, and to a lesser extent, Hawdon) appear to have processes that result in large residuals between predicted catchment load and in-lake TP. As such, these lakes are likely to require further study (and monitoring) to robustly link both the internal and external loads with in-lake conditions, and therefore identify actions (catchment or in-lake) needed to manage water quality. This is outside of the scope of this study and will need to be considered for future management by DOC and Environment Canterbury.

4.3. Sources of modelling uncertainty

A range of factors can contribute to model prediction error when using modelled catchment loads at a whole catchment scale to make predictions of in-lake nutrient dynamics. We have identified, in order of importance, a list of factors thought to contribute to uncertainty in the model predictions, as well as ecological monitoring information that could assist in reducing this error (Table 6).

CLUES predictions – In our opinion the greatest uncertainty remains with model predictions of total annual N and P loads from CLUES for the lake tributary inflows. The CLUES national model has been calibrated with the best available data, but there remain limited data for the small streams that flow into the Canterbury high-country lakes, and therefore calibration data for these types of stream environments are likely to be limited. Particularly for streams draining largely undeveloped catchment area within the DOC estate, we observed relatively large differences between predicted mean stream inflow concentrations and mean nutrient concentrations measured as part of monitoring by DOC. Further investment in monitoring in conservation estate areas, including hydrological monitoring, is recommended to resolve uncertainty of these predictions.

In-lake nutrient recycling – For a small number of lakes, large differences were apparent between predicted and actual in-lake nutrient status. While catchment loads are an important contributor to in-lake nutrient status, in-lake nutrient processing and recycling from lakebed sediments can greatly affect nutrient dynamics, particularly in windy environments that lack macrophyte cover such as those of some high-country lakes. For Lakes Emma and Denny this was thought to be a major contributor, with much higher in-lake nutrient status than would be predicted by catchment loads. Investigation into internal nutrient cycling in these two lakes, and possibly in Lake Clearwater where N predictions were considerably lower than measured, would be needed to be better understand how catchment management could be effective in managing nutrients.

Groundwater contributions – Groundwater inputs are likely to be prevalent for most lakes, but it is uncertain how this may affect in-lake nutrient status. The CLUES model does not specifically consider groundwater transport as a component in the model, and therefore does not differentiate between groundwater and surface water sourced inputs (Samedi-Davies et al. 2016). As part of our modelling, we accounted for some groundwater inputs into Lake Clearwater from the Clearwater Huts tank losses, but this was only a small proportion of the underprediction of TN in Lake Clearwater by catchment loading. It is possible that more significant groundwater inputs occur to some lakes, as has been suggested in previous studies (Wadworth-Watts 2013). Further investigation into groundwater nutrient concentrations in proximity to lake inflows would provide greater certainty, as major effects of groundwater on in-lake nutrient status are more likely to occur where groundwater concentrations are significantly higher than surface water inflows (Kelly et al. 2016).

Waterbird contributions – Seasonal waterbird abundances were adjusted from detailed seasonal monitoring which occurred between 2011 and 2013 reflecting overall trends in annual bird counts that have been observed for the Ashburton Basin. There is a possibility that changes in abundances taken from winter bird counts are not representative of the summer seasonal abundance, which are more important for influencing phytoplankton dynamics and would align with Environment Canterbury's lake monitoring period (between December and May). However, the effects of these adjustments were minor, and in most cases save a few lakes (e.g., Lakes Emily and Emma), waterbird contribution to annual nutrient loads was minor.

Phytoplankton dynamics – Lake Heron was observed to have unusually high phytoplankton biomass relative to its nutrient status, meaning that TN and TP plan targets were generally always met but failed to meet chl-*a* plan objectives. This could suggest that phytoplankton is comprised of a very low N and P content, as a significant proportion of the TN and TP is contained in phytoplankton (Knuuttila et al. 1994). For lakes with atypically high in-lake TN concentrations (e.g., Lakes Denny, Emma, Maori-front), it is possible that the occurrence of some cyanobacteria species such as *Dolichospermum*, which are capable of nitrogen fixing, contributing to nitrogen loads and may account for high TN values (Vanni 2002). Present monitoring of high-country lakes does not include assessment of phytoplankton community composition or nutrient stoichiometry (N and P content of phytoplankton) to inform this. There is also a possibility that some lakes have lower particulate N and P in inflows relative to dissolved nutrients, which are then more immediately taken up by phytoplankton. Further monitoring of phytoplankton community composition and dissolved nutrient fractions in water could assist in this understanding.

Seasonality of monitoring – High-country lake monitoring conducted by Environment Canterbury is operated over the spring to autumn period (Dec-May) which differs from annual loads used by Vollenweider (1982) in his mass balance modelling approach. This results in misalignment of data between measured in-lake concentrations (seasonal) and tributary inflow loads from CLUES that are based on annual means. It is probable that differences are not large and would be lessened by the very short hydraulic residence times of the lakes (range 0.01-0.5 $year^{-1}$). It is, however, acknowledged that seasonality of monitoring data could affect model calibration against annual CLUES catchment load predictions.

Table 5. Sources of error that are thought to contribute to inaccuracy of relating catchment nutrient loads to in-lake nutrient status for the set of Canterbury high-country lakes. Also shown are further monitoring that could help in reducing uncertainty and error in the modelling process.

Sources of modelling error	**Potential impact**	**Ecological data to reduce error and uncertainty**
Inaccuracy of Inflow nutrient loads by CLUES	high	Tributary inflow monitoring- DOC estate land
Internal nutrient recycling and processing	high for some lakes	Water column oxygen dynamics and sediment analyses (lakebed and resuspended), measuring denitrification
Poor hydrological inflow and lake water residence	moderate	Flow monitoring, lake water balance modelling
Groundwater nutrient contributions	moderate	Groundwater quality monitoring and hydrological modelling
Waterbird contributions poorly predicted and seasonally variable	low	Seasonal bird abundance monitoring on priority lakes
Phytoplankton dynamics driven by other factors	low	Phytoplankton monitoring, dissolved nutrients
Seasonal monitoring of in-lake conditions	low	Comparison to annual lake monitoring data for a subset of lakes

4.4. Use of modelling to inform catchment loads

Estimates of load reductions to meet in-lake benchmarks are considered at this stage to provide indicative values of the proportional change in catchment load needed to meet the limits. They suggest that considerable reductions in catchment nutrient loads are required to achieve the current objectives in the regional land and water plan for a majority of lakes. This result was not unexpected, with 5-year mean TN, TP and chl-*a* concentrations well exceeding these objectives. Estimated load reductions to meet plan objectives were generally proportional to requirements for TN and TP concentration reductions, but tended to be slightly greater because of the exponential function of loads with in-lake concentrations (Vollenweider 1982). While there is likely to be some uncertainty in estimates of load reductions, they do provide an approximation of loading changes required, with lakes that were thought to be too uncertain omitted from the calculations.

Overall, the predictions of load changes are thought to be more robust for deep lakes than for shallow lakes, largely due to the greater certainty in model predictions of in-lake nutrient concentrations for deep lakes. There remains uncertainty in the estimated load reductions due to error sources associated with modelling (highlighted in the previous section) and difficulty in forecasting responses of lakes to future load changes. For lakes that were thought to be affected by internal nutrient cycling (Emma, Denny) or other groundwater N sources (Clearwater, Hawdon) we would expect that additional investigations into these processes would need to occur alongside catchment management measures to achieve the plan standards.

The use of CLUES model load outputs to better understand variability in lake sub-catchment nutrient loads is another important use of this spatial modelling tool data that was beyond the scope of this study. For validating CLUES catchment loads with in-lake water quality conditions we only considered the combined loads from all sub-catchments. However, from a lake management perspective, further consideration of spatial variability in loads across the catchment and identifying hotspots of contaminant generation and delivery is equally important. While we have conducted limited validation of reach-scale CLUES load predictions with tributary loads where stream monitoring data were available, sub-catchments identified in CLUES as having high N and P loads would need to be validated with stream nutrient monitoring. Equally there remains uncertainty of CLUES for predicting nutrient losses from tussock grassland areas in the conservation estate. The use of finer scale spatial modelling tools such as Overseer is another important avenue for improving and validating predictions from CLUES, which works at a much broader spatial scale and has more limited land-use information. Further work on comparing these modelling platforms in the high-country lake catchments is a priority for making sound decisions on catchment load targets.

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7. APPENDIX

Appendix 1. In-lake chlorophyll-*a* total nutrient relationships for 27 Canterbury high country lakes.

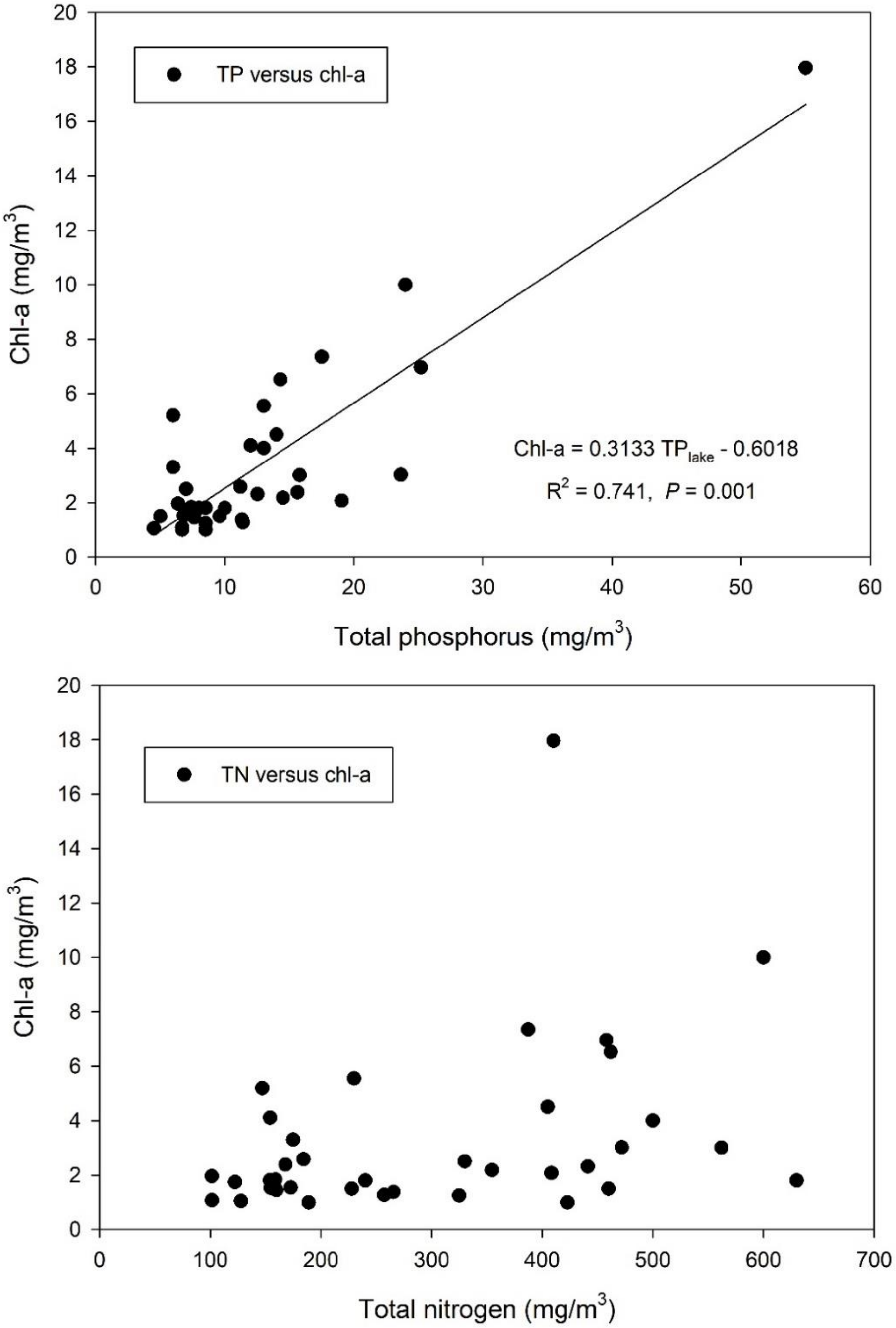

Figure A1.1. Relationship between lake 5-year median chlorophyll-*a* (chl-*a*) concentration and associated median total nitrogen and phosphorus concentrations for 27 Canterbury high-country lakes (combined for 2014 and 2020 monitoring periods). Note that the regression equation for the relationship between chl-*a* and total phosphorus was used to determine associated in-lake TP concentrations necessary to meet median chl-*a* plan limits.