Lake Rotokakahi water quality modelling

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Executive summary

Lake Rotokakahi is an iwi-owned lake, administered by the Lake Rotokakahi Board of Control. The lake has a surface area of 4.4 km^2, a mean depth of 17.5 m, and a catchment of 19.7 km^2 of which most is in exotic forest (46.5%), with some pasture (27.8%) and regenerating native forest and scrub (25.7%). Lake Rotokakahi has only one permanent surface inflow and it is assumed that the lake must be predominantly groundwater fed. The lake outflow, Te Wairoa Stream, flows into Lake Tarawera. Monitoring indicates that water quality has recently declined in the lake, with a shift from a mesotrophic state in the 1990s, to currently being classified as eutrophic. Increased algal biomass has reduced water clarity and in May 2011 the first ever recorded algae bloom of a toxic cyanobacterium species may have resulted in a fish kill in Te Wairoa Stream. With the majority of the catchment in either exotic or native forest, the cause for the decline in water quality is unclear. However there is some concern that forestry harvesting operations may lead to increased surface runoff of sediment and associated phosphorus in ephemeral streams that feed into the lake. The objective of this study was to setup a water quality model for Lake Rotokakahi, which in the future may provide a decision-support tool for lake managers.

The model used, DYRESM-CAEDYM, is a one-dimensional (1D) coupled hydrodynamic-water quality model that has been widely used in New Zealand and overseas. Methodology for deriving model forcing data (e.g. meteorological data, inflow volumes and nutrient loads), including the application of catchment and lake water balances, is described in this report. The catchment water balance indicates that groundwater and rainfall account for 37% and 42%, respectively, of the total inflow volume to the lake, with surface and ephemeral inflows contributing a smaller proportion (c. 20% combined). Furthermore, it appears that groundwater contributes a significant proportion (c. 60 – 70%) of the total nutrient loads, although surface and ephemeral inflows also contribute a significant proportion (34%) of the total phosphorus load. It should be noted that the catchment water balance is based on a very limited dataset, and therefore subject to significant uncertainty.

We simulated the period July 2009 to June 2012 with DYRESM-CAEDYM. Model performance statistics indicated reasonable simulation of water quality for the calibration period, but did not satisfactorily capture the magnitude and dynamics of chlorophyll *a* and some nutrient species over an independent model validation period. There may be a number of reasons for the poor model performance over the validation period. For example, it may be that zooplankton and/or freshwater mussels (kakahi), which were not included in the model configuration, may exert significant grazing pressure on the phytoplankton populations at certain times. Furthermore, the significant uncertainty in the catchment water and nutrient loads most likely will have affected model performance. Nutrient concentrations are routinely monitored only in the surface inflow. There are no measurements of nutrient and sediment loads in ephemeral streams, and there is very limited data on groundwater nutrient concentrations.

In its current form, the DYRESM-CAEDYM model is not suitable for scenario testing of lake management options. It is recommended that effort is directed at quantification of ephemeral and groundwater inflows and their associated nutrient and (particularly for ephemeral inflows) sediment loads. This may be particularly important for ephemeral inflows located close to the lake that may be influenced by forestry harvesting operations. Recent increases in measured total phosphorus and phosphate concentrations in the surface inflow and in the lake, combined with the degradation of water quality that has already occurred over the last 20 years, provides further impetus for addressing this critical information gap. Were new data to become available, opportunities exist for improving the performance of the current model and for developing a three-dimensional coupled hydrodynamic-water quality model (e.g. ELCOM-CAEDYM) with representation of kakahi and/or zooplankton, which may be able to resolve questions pertinent to the functioning of the lake, and to lake and catchment management.

Acknowledgments

We thank Joseph Butterworth and Paul Scholes (Bay of Plenty Regional Council) for provision of field data, and Joseph Butterworth for the use of the photograph on page one of this report. In this study we used the model DYRESM-CAEDYM (version 3.1) developed by the Centre for Water Research, The University of Western Australia. This project was supported financially through the Lake Biodiversity Restoration program funded by the Ministry of Business, Innovation and Employment (Contract UOWX0505) and funding for the Bay of Plenty Regional Council Chair in Lake Restoration.

Table of Contents

List of Tables

List of Figures

Lake Rotokakahi (Photo: Joseph Butterworth)

1 Introduction

Lake Rotokakahi (38° 13' S, 176° 19' E) is an iwi-owned lake, administered by the Lake Rotokakahi Board of Control (Butterworth 2012). The lake has a surface area of 4.4 km^2 and a catchment of 19.7 km^2, of which most is in exotic forest (46.5%), with some pasture (27.8%) and regenerating native forest and scrub (25.7%) (Hamilton et al. 2006). The lake is monomictic, with a mean depth of 17.5 m (maximum depth is 32 m), and has a complex morphology, with two main basins, a small semi-enclosed bay at the western end, and an island in the southwest of the lake (Figure 1). Lake Rotokakahi has only one permanent surface inflow, and although there are a number of ephemeral streams that flow into the lake during periods of rainfall, it is assumed that the lake must be predominantly groundwater fed (Butterworth 2012). The lake outflow, Te Wairoa Stream, flows into Lake Tarawera, 3 km east of Lake Rotokakahi.

Lake water quality was sampled monthly by Bay of Plenty Regional Council between 1990 and 1996, but following this the lake owners denied access to the lake and the Regional Council instead monitored the lake outlet as a proxy for lake water quality from 2000 – present. Water quality sampling in the lake was re-established from 2006 – 2007 and from 2009 – present (Butterworth 2012). The monitoring indicates that water quality has recently declined in the, with a shift from a mesotrophic state in the 1990s, to now being classified as eutrophic (Butterworth 2012). The lake Trophic Level Index (TLI) ranged from 3 to 3.5 between 1990 and 1996, but had increased to c. 4.5 by 2010. The increased algal biomass has reduced water clarity; Secchi depth declined from 6.6 m in the 1990s to between 2 and 4 m between 2009 and 2012. Furthermore, in May 2011 the first ever recorded algae bloom of a toxic cyanobacterium species (*Anabaena lemmermannii*) may have resulted in a trout fish kill in Te Wairoa Stream. Total nitrogen and total phosphorus concentrations in the lake have shown an increasing trend from 1990 to present, and these data indicate that lake lake phytoplankton is likely to have become progressively more nitrogen limited. The causes for the decline in water quality are unclear, as the majority of the catchment is in forest, and there is only one sheep and beef farm bordering the lake. However, forestry harvesting operations have occurred in the catchment including areas immediately surrounding the lake in recent years, which may be expected to lead to increased surface runoff of sediment and associated phosphorus in ephemeral streams, perhaps elevating total phosphorus concentrations in the lake (Hamilton 2005, Butterworth 2012).

The recent water quality decline in Lake Rotokakahi has prompted concern about the functioning of the lake ecosystem, which includes a relatively healthy population of a freshwater mussel, kakahi (*Hyridella menziesii*). Ecological models may be used to simulate current lake condition and assess the potential impact of changes to climate, land use in the catchment, and/or nutrient loads from various sources, effectively providing a decision-support tool to lake managers. This report describes the setup and calibration of a one-dimensional (1D) hydrodynamic-ecological model for Lake Rotokakahi. This report is intended as a guide to the model setup and application, and identifies current constraints and information gaps that likely affect the model performance. If these data gaps are addressed in future then it may be possible to simulate lake management scenarios to explore the potential impacts of, for example, land use practices on lake water quality.

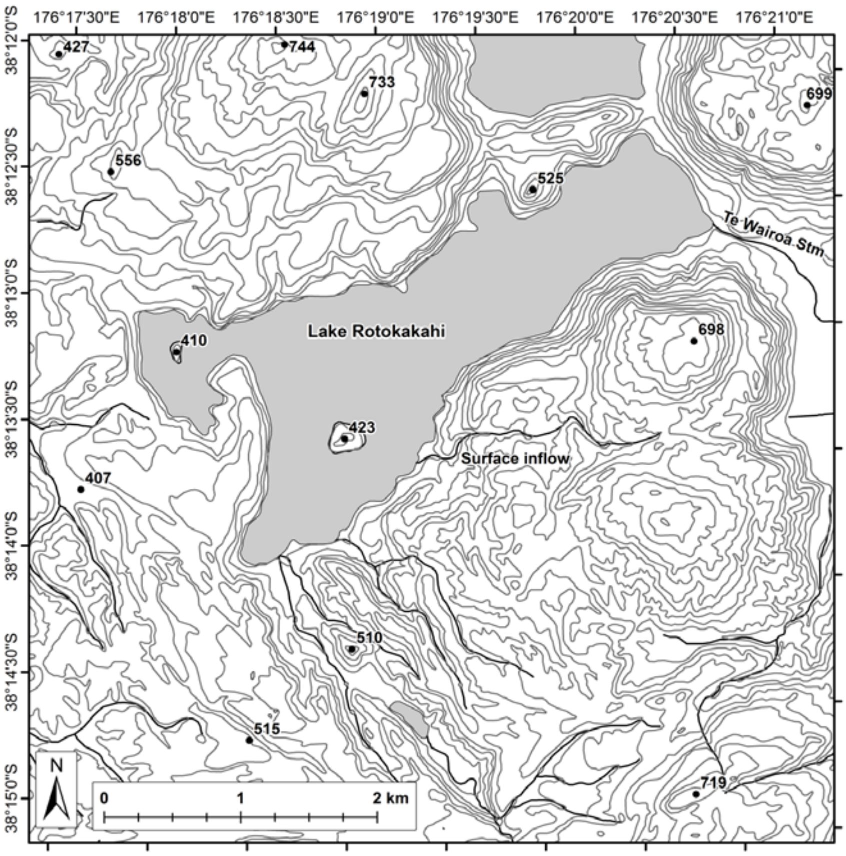

Figure 1: Lake Rotokakahi and surrounding topography. Black circles mark elevation above sea level (m), and location of permanent surface inflow and the lake outlet (Te Wairoa Stm) are indicated on the map. Note surface inflows to the south of the lake are ephemeral inflows only.

2 Methods

2.1 DYRESM-CAEDYM model description and configuration

In this study, the one-dimensional (1D) hydrodynamic model DYRESM (version 3.1.0-03) was coupled with the aquatic ecological model CAEDYM (version 3.1.0-06), both developed at the Centre for Water Research, University of Western Australia, to simulate water quality in Lake Rotokakahi. DYRESM resolves the vertical distribution of temperature and density, and the vertical mixing processes in lakes and reservoirs. CAEDYM simulates time-varying fluxes that regulate biogeochemical variables (e.g. nutrient species, phytoplankton biomass). The model includes comprehensive process representations for carbon, nitrogen, phosphorus, and dissolved oxygen cycles, and inorganic suspended solids. Many applications have been made of DYRESM-CAEDYM to different lakes, including several lakes in the Rotorua region (e.g. Burger et al. 2008, Gal et al. 2009, Özkundakci et al. 2011) and detailed descriptions of the model equations can be found in Robson and Hamilton (2004) and Romero et al. (2004).

The biogeochemical variables in CAEDYM may be configured according to the goals of the model application and availability of data. In this study, three groups of phytoplankton were included in CAEDYM, based on monitoring data from Lake Rotokakahi that showed chlorophytes to be dominant throughout much of the year, with occasionally dominance of diatoms and cyanophytes (Butterworth 2008). The interactions between phytoplankton growth and losses, sediment mineralisation and decomposition of particulate organic matter influence nitrogen and phosphorus cycling in the model. Fluxes of dissolved inorganic and organic nutrients from the bottom sediments are dependent on temperature and concentrations of dissolved oxygen of the water layer immediately above the sediment surface. Model parameters are calibrated to be specific to each new application but with an extensive parameter library now available from the large number of studies undertaken with DYRESM-CAEDYM. Parameters used in this study are given in Appendix A.

The input data required for DYRESM-CAEDYM include meteorological forcing, lake inflow and outflow volumes, measurements of lake inflow water temperature, dissolved oxygen and nutrient concentrations, and in-lake measurements of water temperature, dissolved oxygen, nutrient concentrations and chlorophyll *a* concentration (a proxy for phytoplankton biomass). The simulation period for the Lake Rotokakahi DYRESM-CAEDYM model was from July 2009 to June 2012, as during this period there were water quality measurements available for both the lake inflow and the lake itself. Water quality in the lake has been sampled monthly by Bay of Plenty Regional Council between 1990 and 1996, and from 2009 – present, with a period of additional sampling during 2006 – 2007 as part of a University of Waikato student's MSc research (Butterworth 2012). However, there is only limited data available on the water quality of lake inflows. The one permanent surface inflow has been monitored monthly for total nitrogen, total phosphorus, nitrate, ammonium and phosphate between April and September 2007 (Butterworth 2008), and then from 2009 – present (by Bay of Plenty Regional Council).

In this study, DYRESM-CAEDYM was run at hourly time steps between July 2009 and June 2012, with daily averaged input data and daily output data at midday. The period July 2009 – June 2011 was used for model calibration, and July 2011 – June 2012 for model validation.

2.2 Meteorological input

Meteorological data required for the simulation period were obtained from the National Climate Data Base (http://cliflow.niwa.co.nz) for Rotorua airport climate station (36°0.6' S, 176°19' E), which is located c. 10 km north of Lake Rotokakahi. The data included air temperature (°C), shortwave radiation (W m^{-2}), vapour pressure (hPa), wind speed (m s^{-1}) and rainfall (m) (Figure 2). Data are collected at Rotorua airport at hourly intervals, and for the purposes of the model input were standardised to daily average values except for rainfall, which was provided as a daily total value. Daily values for theoretical clear sky and full cloud-cover shortwave radiation (W m^{-2}) were estimated by fitting seasonal sinusoidal curves to the maximum and minimum observed daily shortwave radiation values across the entire simulation period. Subsequently, average daily cloud cover was estimated by calculating the percentage difference between observed total daily shortwave radiation and the estimated theoretical daily maximum and minimum. Occasional values below 0 (clear sky) or above 1 (full cloud cover) were set as 0 and 1, respectively.

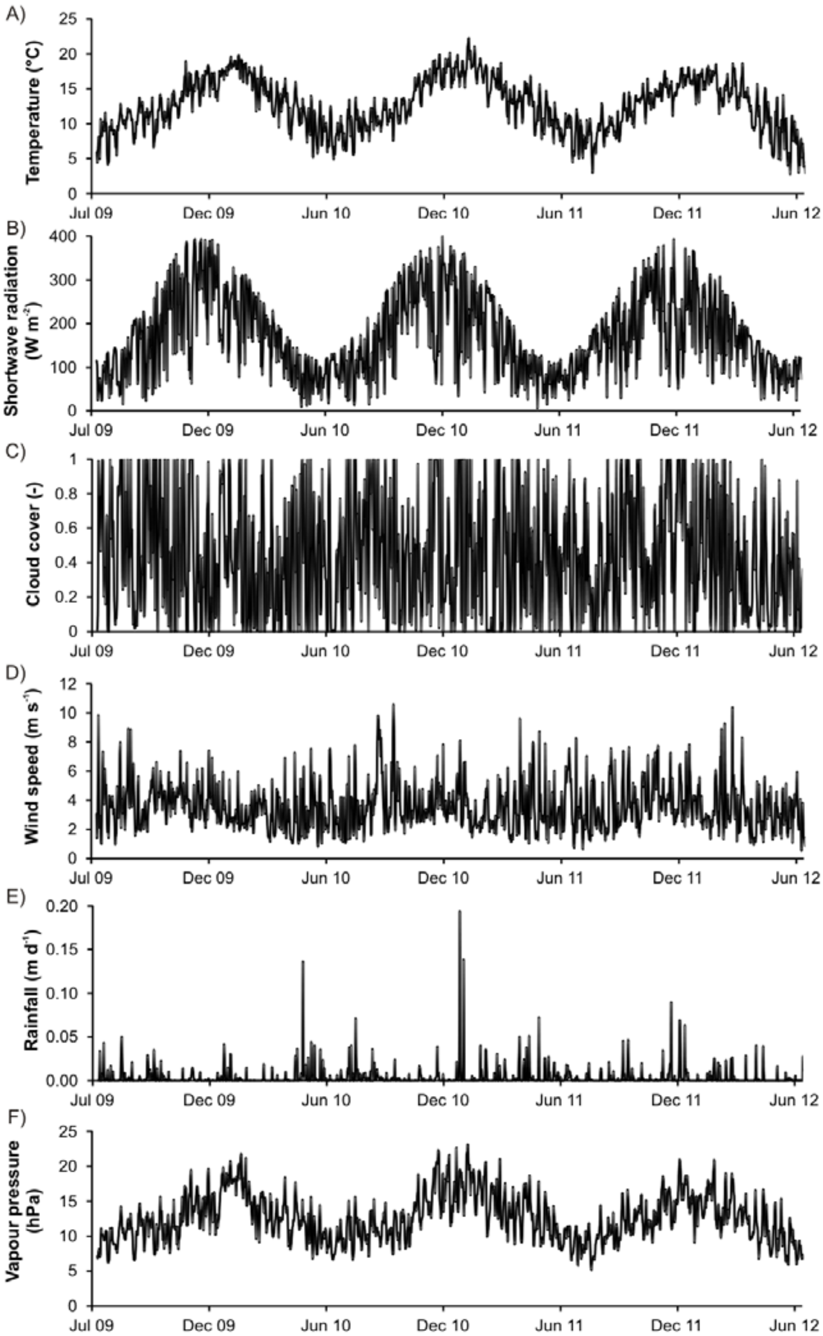

Figure 2: Meteorological data used as input to the DYRESM-CAEDYM model (July 2009 – June 2012). A) Air temperature (°C), B) shortwave radiation (W m^{-2}), C) cloud cover (fraction of whole sky), D) wind speed (m s^{-1}), E) rainfall (m day^{-1}) and F) vapour pressure (hPa). Data were obtained from the Rotorua airport climate station.

2.3 Catchment water balance

A catchment water balance was used to estimate inflows into Lake Rotokakahi. The catchment area is 19.7 km^2, of which most is in exotic forest (46.5%), with some pasture (27.8%) and regenerating native forest and scrub (25.7%) (Hamilton et al. 2006) (Table 1). The lake is predominantly groundwater fed but has one permanent surface inflow and several ephemeral streams.

Table 1: Land use in the Lake Rotokakahi catchment and predicted nitrogen (N) and phosphorus (P) loads (from Hamilton et al., 2006).

Land use	Area (ha)	N loss (kg ha^{-1} y^{-1})	P loss (kg ha^{-1} y^{-1})	N load (t y^{-1})	P load (t y^{-1})
Pasture	548	7	1	3.84	0.55
Native forest	507	2.5	0.4	1.27	0.20
Exotic forest	917	2.5	0.4	2.29	0.37
Lake (rainfall)	433	3.96	0.148	1.71	0.06
Total (inc. rainfall)	2404	-	-	9.11	1.18
Total (exc. rainfall)	1971	-	-	7.39	1.12

Total surface and groundwater inflows were calculated as rainfall in the catchment minus evapotranspiration. Evapotranspiration was estimated separately for pasture and forest, using a sinusoidal pattern to account for seasonal variation. For pasture, evapotranspiration was estimated to range between 30% of rainfall in winter and 90% in summer (mean = 60%). For native and exotic forest evapotranspiration was estimated to range between 40% of rainfall in winter and 120% in summer (mean = 80%). To determine the relative proportion of surface and groundwater inflows, we used predicted total phosphorus and total nitrogen inflow masses (Hamilton et al. 2006), and measurements of nutrient concentrations in the surface inflow and groundwater to prescribe daily values for surface, ephemeral and groundwater inflows (see Section 2.5.3 for details on inflow nutrient concentration parameterisation). To estimate inflow from ephemeral streams we set a rainfall threshold of > 10 mm day^{-1}, and calculated the ephemeral runoff as 70% of total surface runoff. We iterated the nutrient mass flux equation (Equation 1) until we had the best match between predicted nutrient loads (Table 1) and calculated nutrient loads in lake inflows (Table 2).

$$\boldsymbol{M = x_1 C_{gw} + x_2 C_{sf} + x_3 C_{eph}}$$

Equation 1

Where, M = nutrient load (g day^{-1}), x_1, x_2, and x_3 are the iterated volumes for the groundwater, surface and ephemeral inflows, respectively (m^3 day^{-1}), and C_{gw}, C_{sf}, and C_{eph} are the nutrient (nitrogen or phosphorus) concentration in the groundwater, surface and ephemeral inflows, respectively (g m^{-3}).

The mean annual inflow volumes and nutrient loads for the Lake Rotokakahi DYRESM-CAEDYM model are detailed in Table 2. Groundwater and rainfall account for 37% and 42% of the total inflow volume, respectively, with surface and ephemeral inflows contributing a smaller proportion (c. 20% combined). Groundwater contributes a significant proportion (c. 60 – 70%) of the total nutrient loads, although surface and ephemeral inflows also contribute a significant proportion (34%) of the total phosphorus load.

Table 2: DYRESM-CAEDYM model input inflow volumes and nutrient loads into Lake Rotokakahi

	Inflow volume $m^3\ y^{-1}$	% of total	TN load $t\ y^{-1}$	% of total	TP load $t\ y^{-1}$	% of total
Surface inflow	2987063	18.61	0.77	8.45	0.34	28.93
Ephemeral inflow	399610	2.49	0.11	1.17	0.05	3.85
Groundwater	6000825	37.38	6.53	71.41	0.72	61.52
Rainfall	6665817	41.52	1.73	18.96	0.07	5.70
Total (inc. rainfall)	16053315		9.14		1.17	
Total (exc. rainfall)	9387498		7.41		1.10	

2.4 Lake water balance

A water balance was calculated for Lake Rotokakahi using inflows derived from the catchment water balance, and hydrological and meteorological data available for the lake and catchment over the simulation period, such that:

$$\Delta S = I_{sf} + I_{eph} + I_{gw} + I_r - E_l - O_f$$

Equation 2

Where, ΔS is change in storage in $m^3\ d^{-1}$, I_{sf}, I_{eph} and I_{gw} are surface, ephemeral and groundwater inflows, respectively ($m^3\ d^{-1}$), I_r is rainfall ($m^3\ d^{-1}$), E_l is evaporation from the lake ($m^3\ d^{-1}$), and O_f is outflow from the lake ($m^3\ d^{-1}$).

Change in lake storage (ΔS) was calculated from water level measurements provided by BoPRC, multiplied by the water level-dependent lake area derived from the lake hypsographic curve (Figure 3), and a 30-day running average was used to smooth the step changes between measurements.

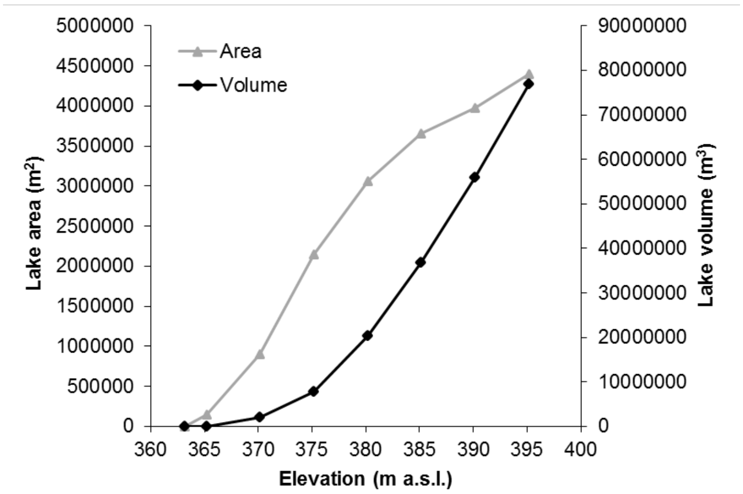

Figure 3: Lake Rotokakahi hypsograph. N.B. Surface of lake at c. 395 m above sea level (m a.s.l.)

Evaporation from the lake was calculated as a function of wind speed and air vapour pressure from the daily average evaporative heat flux (Fischer *et al.*, 1979; Eqn. 6.20 in Imerito (2007)) using meteorological data and water temperature:

$$Q_{lh} = minimum\left(0 \geq \frac{0.622}{P} C_L \rho_A C_E U_A (e_A - e_S(T_S))\Delta t\right)$$

Equation 3

Where, Q_{lh} is the evaporative heat flux in J m^{-2} s^{-1}, P is atmospheric pressure in hPa, C_L is the latent heat transfer coefficient for wind speed at a height of 10 m (1.3 x 10^{-3}), ρ_A is the density of air in kg m^{-3}, L_E is the latent heat evaporation of water (2.453 x 10^{6}) in J kg^{-1}, U_a is the wind speed at 10 m height above ground level in m s^{-1}, $e_S(T_S)$ the saturation vapour pressure at the water surface temperature in hPa, e_a is the vapour pressure of the air in hPa. The condition that Q_{lh} < 0 assumes that condensation does not occur.

For the purposes of determination of water evaporated from the lake surface, a surface lake water temperature was estimated from an empirical relationship between lake surface temperature and 3-day averaged air temperature. The saturated vapour pressure $e_S(T_S)$ is calculated via the Magnus-Tetens formula (TVA, 1972; Eqn. 4.1 in Imerito (2007)):

$$e_S(T_S) = exp\left(2.3026\left(\frac{7.5T_S}{T_S + 237.3} + 0.7858\right)\right)$$

Equation 4

Where, T_s is the water surface temperature in ^{o}C. Lake water temperature can be derived from continuous measurements or estimated (e.g. from daily air temperature and available *in situ* lake water temperature measurements).

The change in mass in the surface layer (layer N) due to latent heat flux is then calculated as:

$$\Delta M_N^{lh} = \frac{-Q_{lh} A_N}{L_V}$$

Equation 5

Where, ΔM_N^{lh} is the change in mass in kg s^{-1}, A_N is the surface area of the lake in m², and L_V is the latent heat of vaporisation for water (2.258 x 10^{6} J kg^{-1}).

Outflow from Lake Rotokakahi was derived as the residual of the otherwise complete water balance (Equation 2) using measured rainfall and storage change, inflows derived from the catchment water balance, and evaporation calculated using Equations 3 - 5. The derived outflow was used for the DYRESM-CAEDYM simulation period, and simulated lake level closely matched BoPRC water level measurements (Figure 4, Pearson's R = 0.86, MAE = 0.04 m).

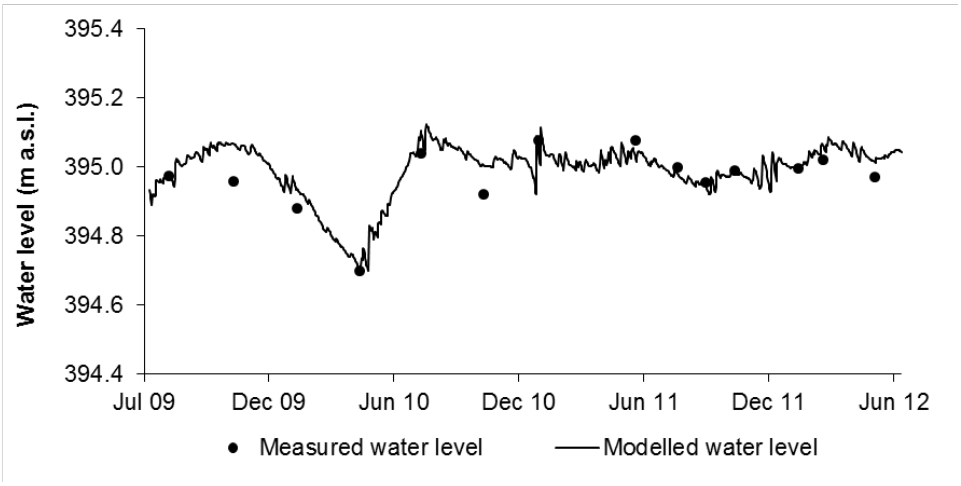

Figure 4: Modelled Lake Rotokakahi water level (black line) and measured water level (black circles) for DYRESM-CAEDYM simulation period (July 2009 – June 2012)

2.5 Inflow parameterisation

2.5.1 Temperature

The temperature of rainfall, surface and ephemeral inflows were set to estimated lake surface temperature, which was derived by linear correlation of air and water temperature measurements, yielding the relationship:

$$T_s = (1.1092 \times T_{air}) + 1.625$$

Equation 6

Where, T_s is the derived water temperature in °C, and T_{air} is measured air temperature in °C.

Temperature of the groundwater inflow was estimated using a previously derived equation for estimating temperature of the Hamurana groundwater spring flowing into Lake Rotorua:

$$T_s = A\cos(\omega t + \sigma) + T_0$$

Equation 7

Where, T_s is the derived water temperature in °C, A is the amplitude in m, ω is the angular frequency (2π/365), σ is the phase angle, T_0 is the mean water temperature in °C, and t is time in days. A lag time of 2 months was applied to account for the delayed response of groundwater temperature to changes in air temperature.

2.5.2 Dissolved oxygen

Dissolved oxygen concentration in lake inflows were estimated as a function of water temperature (Benson and Krause 1980):

$$DO = \exp(7.71 - 1.31\ln(T + 45.93))$$

Equation 8

Where, DO is dissolved oxygen in mg L^{-1}, and T is water temperature in °C. Dissolved oxygen concentration in the groundwater inflow was reduced by 20%.

2.5.3 Nutrients

The one permanent surface inflow into Lake Rotokakahi has been monitored c. monthly for total nitrogen (TN), total phosphorus (TP), nitrate (NO_3), ammonium (NH_4) and phosphate (PO_4). Daily values for the surface inflow were derived by linear interpolation between monthly samples. This method has been used in other model applications (e.g. Burger et al. 2008, Özkundakci et al. 2011, Trolle et al. 2011) but potentially underestimates the effect of storm events that may not be captured by routine monitoring. In the absence of field data on nutrient speciation of labile organic nitrogen and phosphorus concentrations (ONL and OPL, respectively), these species were calculated from monthly stream nutrient measurements of total nutrient concentrations, and were evenly divided into ammonium, dissolved (D) and particulate (P) fractions using the equations:

$$DONL\ or\ PONL\ = \frac{(TN - NO_3 - \ NH_4)}{2}$$

Equation 9

$$DOPL\ or\ POPL = \frac{(TP - \ PO_4)}{2}$$

Equation 10

As in previous DYRESM-CAEDYM applications labile dissolved and particulate organic carbon (DOCL and POCL) concentrations were calculated using inflow labile organic nitrogen concentrations and a Redfield molar ratio of 106: 16 for C: N.

$$DOCl\ or\ POCL = \frac{(DONL\ or\ PONL \times 106 \times 12)}{(16 \times 14)}$$

Equation 11

In the absence of any monitoring data for ephemeral streams, daily values for nutrient concentrations were set to be the same as for the surface inflow.

Few empirical data are available for groundwater inflow nutrient concentrations in the Rotokakahi catchment. Groundwater nutrient concentrations collected from one bore southwest of the lake indicated that nitrate concentrations ranged from 0.02 to 1.9 mg L^{-1} and dissolved reactive phosphorus ranged from 0.04 to 0.07 mg L^{-1} (Janine Barber (BoPRC) and Abigail Lovett (GNS), pers. comm.). Groundwater was assigned constant nutrient concentrations equal to the mean concentration for the depths surveyed, and was assumed to be devoid of any organic nutrients.

Rainfall dissolved inorganic nutrient concentrations were estimated using available literature values for atmospheric deposition rates. Atmospheric inputs in rain for the Bay of Plenty or central North Island have been reported to be between 1.5 and 3.5 kg N ha^{-1} yr^{-1}, and between 0.17 and 0.2 kg P ha^{-1} yr^{-1} (Hamilton 2005, Parfitt et al. 2006, Parfitt et al. 2008). Rainfall was assumed to be devoid of any organic nutrients.

2.6 DYRESM-CAEDYM calibration and validation

DYRESM-CAEDYM was calibrated against field data (monthly samples collected by BoPRC) over the two-year period between July 2009 and June 2011 for variables of temperature, DO, chlorophyll *a*, PO_4, TP, NH_4, NO_3, and TN, at the water surface (0 m), and at depths of 15 m and 28 m. The three simulated phytoplankton groups (i.e. cyanophytes, chlorophytes and diatoms) collectively contributed to a total simulated chlorophyll *a* concentration, which was calibrated against measured chlorophyll *a*. Model parameters were adjusted manually using a trial and error approach with values set to within literature ranges (e.g. Schladow and Hamilton 1997, Özkundakci et al. 2011, Trolle et al. 2011). The model error was represented by a series of model performance statistics, including the Pearson correlation coefficient (R), the mean absolute error (MAE), and comparison of the means of both the observations ($Mean_{obs}$) and model output ($Mean_{mod}$).

Correlation, often measured with a correlation coefficient, indicates the strength and direction of a linear relationship between two variables (for example model output and observed values). A number of different coefficients are used for different situations. The best known, which was used in this study, is the Pearson product-moment correlation coefficient (also called Pearson correlation coefficient or the sample correlation coefficient), which is obtained by dividing the covariance of the two variables by the product of their standard deviations. For a series of n observations and n model values, the Pearson product-moment correlation coefficient can be used to estimate the correlation between model and observations:

$$R = \frac{\sum_{i=i}^{n}(x_i - \bar{x}) \times (y_i - \bar{y})}{\sqrt{\sum_{i=i}^{n}(x_i - \bar{x})^2 \times \sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

Equation 12

Where, y_i is observed values and x_i is modelled values at time/place i. The correlation is +1 in the case of a perfect increasing linear relationship, and -1 in case of a perfect decreasing linear relationship, and the values in between indicate the closeness of fit to a linear relationship between, for example, model and observations. In modelling, a correlation coefficient between simulations and observations of +1 may be ideal, whereas 0 means the there is no linear relationship amongst variables, and -1 represents the poorest possible model fit. However, the correlation between model output and field observations can approach 1 whether or not there is a consistent offset between the two.

The MAE is a measure of average error magnitude, which derives from the unaltered magnitude (absolute values) of each difference:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|x_i - y_i|$$

Equation 13

The calculated MAE values have units, and MAE for phosphorus concentrations, for example, cannot for this reason be compared directly to MAE values for chlorophyll *a* concentrations. However, MAE values can be used to distinguish model performance or a variable in a calibration period with that of a validation period, as well as to compare the individual model performance to that of other predictive models.

For each output variable the model statistics were quantified after each simulation for which model parameter values were adjusted. Calibration continued until there was negligible improvement in model statistics with repeated model simulations. Model statistics were also compared to modelling studies in the literature to assess an acceptable model error for prediction purposes. The final model parameters from the calibration were then fixed for model validation over the period July 2011 – June 2012.

3 Results and discussion

3.1 DYRESM-CAEDYM calibration and validation

The model parameters adjusted during the calibration of DYRESM-CAEDYM are included in Appendix A. Parameter values were assigned within the range found in the literature (e.g. Schladow and Hamilton 1997, Burger et al. 2008, Trolle et al. 2011). Visual comparisons of modelled temperature, dissolved oxygen, NH_4, TN, TP, NO_3, PO_4, and total chlorophyll *a* with available field measurements at 0 m, 15 m and 28 m depth are shown in Figure 5 - Figure 7. The overall model performance was assessed statistically using Pearson's R, MAE, and the mean of both the field observations and modelled values (Table 3). These values suggest that, for the calibration period at least, the model was able to reproduce the magnitude and dynamics of field measurements, and performed reasonably well compared to other published model applications for other Rotorua lakes (e.g. Burger et al. 2008, Özkundakci et al. 2011, Trolle et al. 2011). The model simulated phytoplankton groups approximately in accordance with the results of phytoplankton sampling by Butterworth (2008); chlorophytes dominated throughout much of the year, particularly at the surface, but diatoms were more dominant in winter, and cyanophytes (at the surface) in late summer (Figure 8). The model also indicates the presence of a deep chlorophyll maximum (DCM), primarily composed of diatoms, with some chlorophytes, at around 10 - 15 m depth. Measured data also indicates that chlorophyll *a* concentration at 15 m depth often exceeded that at the surface.

Comment [Anon1]: There are fluorescence profiles that also demonstrate this.

During the calibration period the model performed well at simulating some variables, such as temperature, dissolved oxygen, chlorophyll *a*, NH_4 and PO_4, particularly at 15 m and 28 m. At the surface, NH_4 was typically underestimated and chlorophyll *a* slightly overestimated. Also, according to field measurements, dissolved oxygen at the surface was overestimated by the model for the calibration period, although the field data seems anomalously low for surface measurements during this period (i.e. well below 100% saturation). The model performed less well at simulating other variables, such as TN and NO_3, with the model typically underestimating NO_3 at the surface and 15 m, and overestimating NO_3 at 28 m.

Comment [Anon2]: Joe Butterworth could check with Paul Scholes on this.

For the validation period, the model was less successful at capturing the magnitude and dynamics of field measurements. Although the model performed well at simulating temperature, dissolved oxygen and (at some depths) NH_4, NO_3, the model did not perform well at simulating variables such as chlorophyll *a*, TN and TP. In particular, the model simulated a phytoplankton bloom (c. 20 µg L^{-1}) in spring 2011 at a time when field measurements suggested that chlorophyll *a* concentrations were low (< 1 µg L^{-1}). The reasons for the poor performance of the model during the validation period are unclear, but it should be noted that there was limited data available for parameterising inflow volumes and nutrient concentrations, which will likely affect the accuracy of model simulations, particularly with regard to timing of phytoplankton blooms if driven by influxes of nutrients from external sources. Also, biota that can potentially exert control on phytoplankton biomass (e.g. zooplankton and kakahi) were not included in the model due to limited data with which to constrain model parameters and validate model output. We attempted to compensate for the effect of zooplankton grazing on phytoplankton by slightly elevating values for the phytoplankton respiration rates. This will not capture the dynamic effect of variable zooplankton biomass on phytoplankton populations, or the effect of phytoplankton succession on zooplankton dynamics. Zooplankton abundance in Lake Rotokakahi may be highly variable. For example, densities ranged between 0 and c. 400 ind. L^{-1} between September 2006 and September 2007 (Butterworth 2008). It is possible that the low measured chlorophyll *a* concentrations during late 2011 may be due to grazing by zooplankton and/or kakahi, which was not captured by the current model application.

3.2 Limitations

As indicated earlier in this report, there are a number of limitations associated with both the conceptual complexity of this application of DYRESM-CAEDYM and model forcing data. Although conceptual simplifications of a system being modelled are unavoidable (Harris 1994), omission of species and processes may affect model output. In the case of Lake Rotokakahi it is possible that omission of zooplankton and kakahi, both of which may have potential to exert control on phytoplankton biomass, may have influenced the simulation of chlorophyll *a* concentrations. Inclusion of these two groups in the model, should sufficient data become available for model parameterisation and calibration, may improve model performance but it is important to note that increasing model complexity contributes to uncertainty in model output (e.g. Loucks et al. 2005).

DYRESM is a one-dimensional (1D) hydrodynamic model that represents a lake as a series of vertical layers. Application of DYRESM to a particular waterbody assumes that vertical variations in the water column are greater than horizontal variability (Imerito 2007). This assumption may not be valid for Lake Rotokakahi, which has a complex morphology, with two main basins and a small bay at the western end of the lake, thus the model is unlikely to be able to capture localised features. Horizontal variability in ecological variables has been observed in the lake, such as when cyanobacteria blooms are driven by the wind to aggregate at one end of the lake (Butteworth, pers.comm.). However, with only one in-lake sampling station there are limited field data to quantify horizontal variability (but see Butterworth 2008).

DYRESM-CAEDYM requires input data at a daily time step and resolves processes at an hourly timescale. Input data for ecological models are almost always available only on a coarser time scale, and in this case there were very limited data on the volumes and water quality of surface and groundwater inflows into the lake. There is significant uncertainty associated with the catchment water balance used to derive surface, ephemeral and groundwater inflows. Measurements of surface and ephemeral inflows are required to improve our estimation of the relative contribution of these inputs to the lake water balance, however.

Although the permanent surface inflow is monitored monthly for nutrients, there are no measurements for ephemeral surface inflows, which would be associated with storm events, and may carry high nutrient and sediment loads. In other catchments, storm flow events have been shown to transport large amounts of total nitrogen, total phosphorus and sediments (Abell et al. 2013). Monthly monitoring of the surface inflow would also be unlikely to capture the influence of high rainfall events on nutrient loads, although this inflow is likely to be predominantly groundwater-fed (Butterworth 2008). However, there is also significant uncertainty around the nutrient concentrations assigned to groundwater in the model, which were derived from measurements made in one bore. The inflow monitoring could also extend to better understanding the impact of forestry on discharge and nutrient and sediment concentrations in the lake. Satellite images have been used to provide some preliminary indication of areas that have been harvested in the forested part of the catchment over the past c. 12 years (M. Allan, pers. comm.) but there is considerable work required to then prescribe changes in discharge, sediment and nutrients arising from these areas over the duration of a harvesting cycle.

Finally, meteorological forcing data was derived from the climate station at Rotorua airport. Lake Rotokakahi is more sheltered than Lake Rotorua and thus wind speeds measured at Rotorua may not be applicable to Rotokakahi. As wind influences thermal dynamic and mixing in DYRESM-CAEDYM, it is possible that model output (including nutrient and phytoplankton concentrations) may be affected by uncertainties in the meteorological forcing data

3.3 Potential for modelling other biota

There are modules for zooplankton and bivalves in CAEDYM, theoretically enabling inclusion of these two groups in the model. However, inclusion of zooplankton would require temporally resolved data to be collected on zooplankton abundance and species composition, and there are only very limited data currently available on zooplankton in Lake Rotokakahi. Sampling was undertaken between September 2007 and September 2008, which showed high abundances of cladocerans and rotifers in spring and summer, with much lower numbers in winter (Butterworth 2008). However, to our knowledge there has been no zooplankton sampling since that time. Adequate simulation of zooplankton in the DYRESM-CAEDYM model would ideally require several years of zooplankton data with which to calibrate and validate the model.

It is possible to model benthic biota (such as the freshwater mussel, kakahi) in DYRESM-CAEDYM, but preliminary modelling with a benthic bivalve group included revealed the model to be highly unstable. The model typically became unstable when the number of layers changed very rapidly (e.g. at the onset or breakdown of stratification) and it seems likely that there may be some difficulties with the way DYRESM manages the rapid change in layers and partitioning of the benthic variable biomass into those layers. Although modelling kakahi using DYRESM-CAEDYM may not be suitable for this application, bivalves have been modelled effectively using CAEDYM and a three-dimensional hydrodynamic driver (i.e. ELCOM), which has a fixed vertical grid and therefore is unlikely to have the same stability issues (Spillman et al. 2008, Bocaniov et al. 2013). Further research could focus on a 3D model for Lake Rotokakahi that includes a freshwater mussel group, but it should be noted that this will require substantial resources to properly calibrate and validate such a complex and highly spatially resolved ecological model. However, were such a model to be developed it could provide insight into the impact of water quality stressors (e.g. low dissolved oxygen concentrations) on a culturally and ecologically significant species.

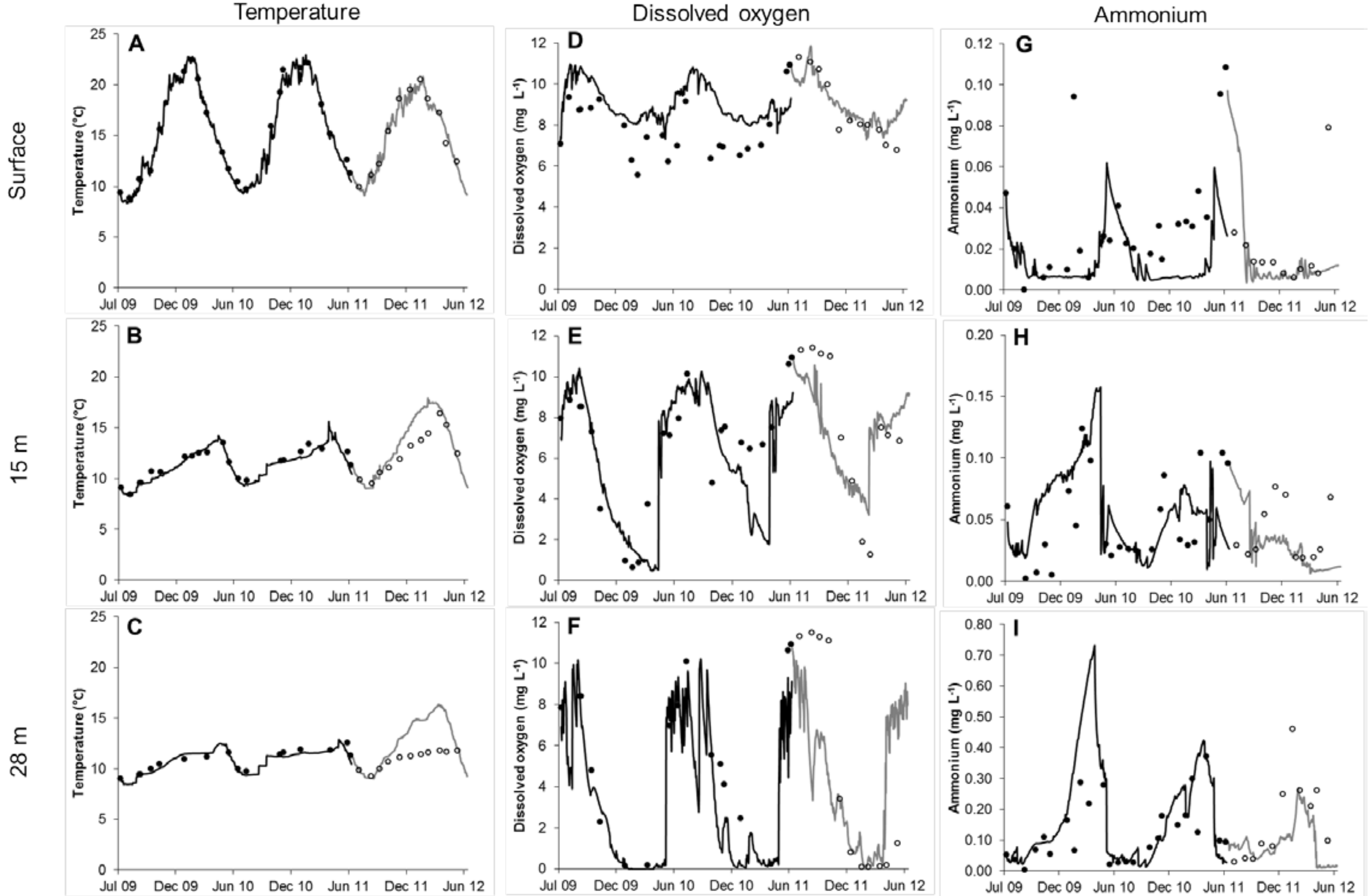

Figure 5: Modelled (DYRESM-CAEDYM) variables (black line = calibration and grey line = validation period) compared with field data (filled circles = calibration and open circles = validation period). A), B) and C) Temperature (°C) at 0 m, 15 m and 28 m depth, respectively. D), E), and F), Dissolved oxygen (mg L^{-1}) at 0 m, 15 m and 28 m depth, respectively. G), H) and I) Ammonium (NH_4, mg N L^{-1}) 0 m, 15 m and 28 m depth, respectively.

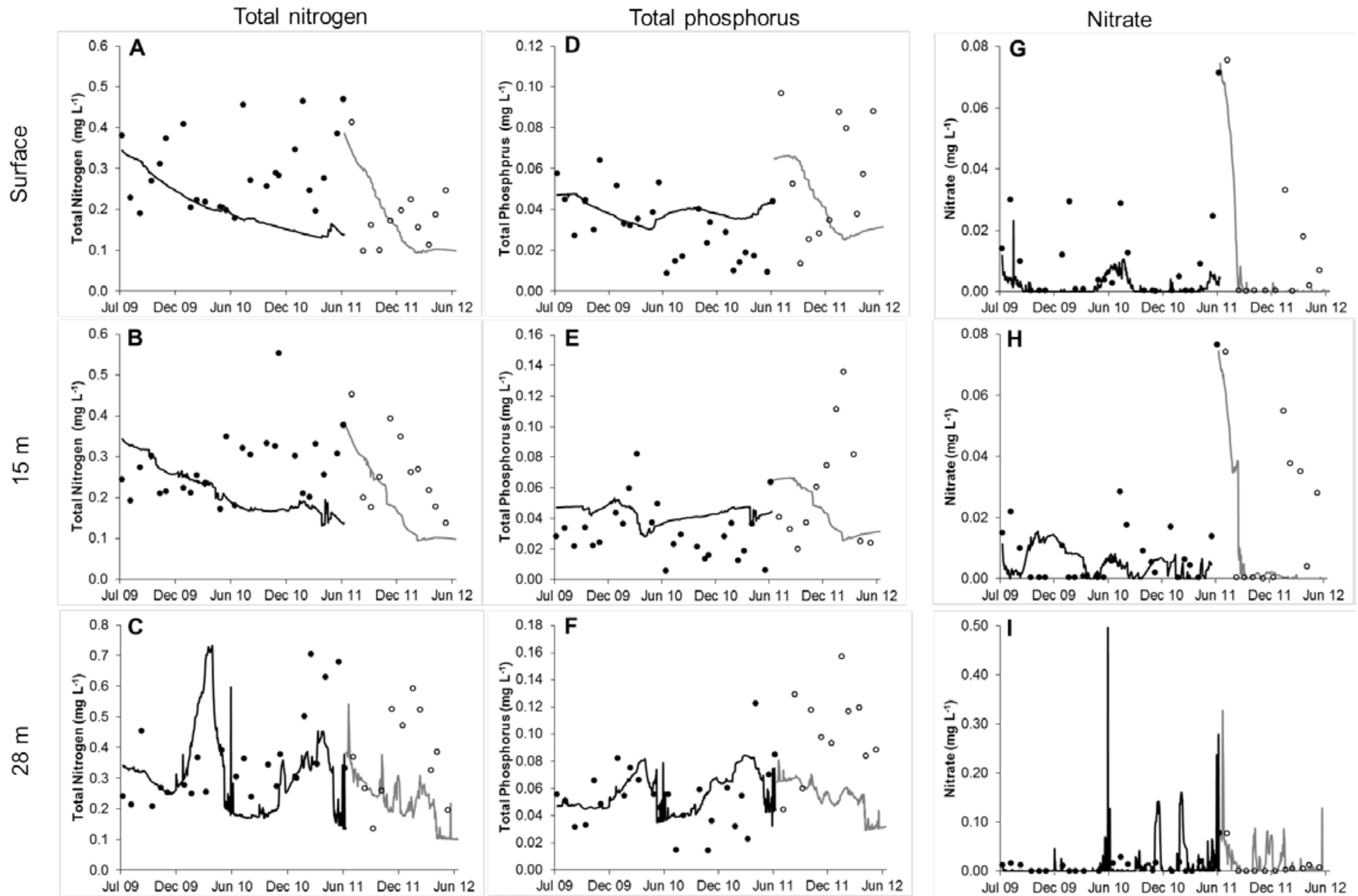

Figure 6: Modelled (DYRESM-CAEDYM) variables (black line = calibration and grey line = validation period) compared with field data (filled circles = calibration and open circles = validation period). A), B) and C) Total nitrogen (mg L^{-1}) at 0 m, 15 m and 28 m depth, respectively. D), E), and F) Total phosphorus (mg L^{-1}) at 0 m, 15 m and 28 m depth, respectively. G), H) and I) Nitrate (NO_3, mg N L^{-1}) 0 m, 15 m and 28 m depth, respectively.

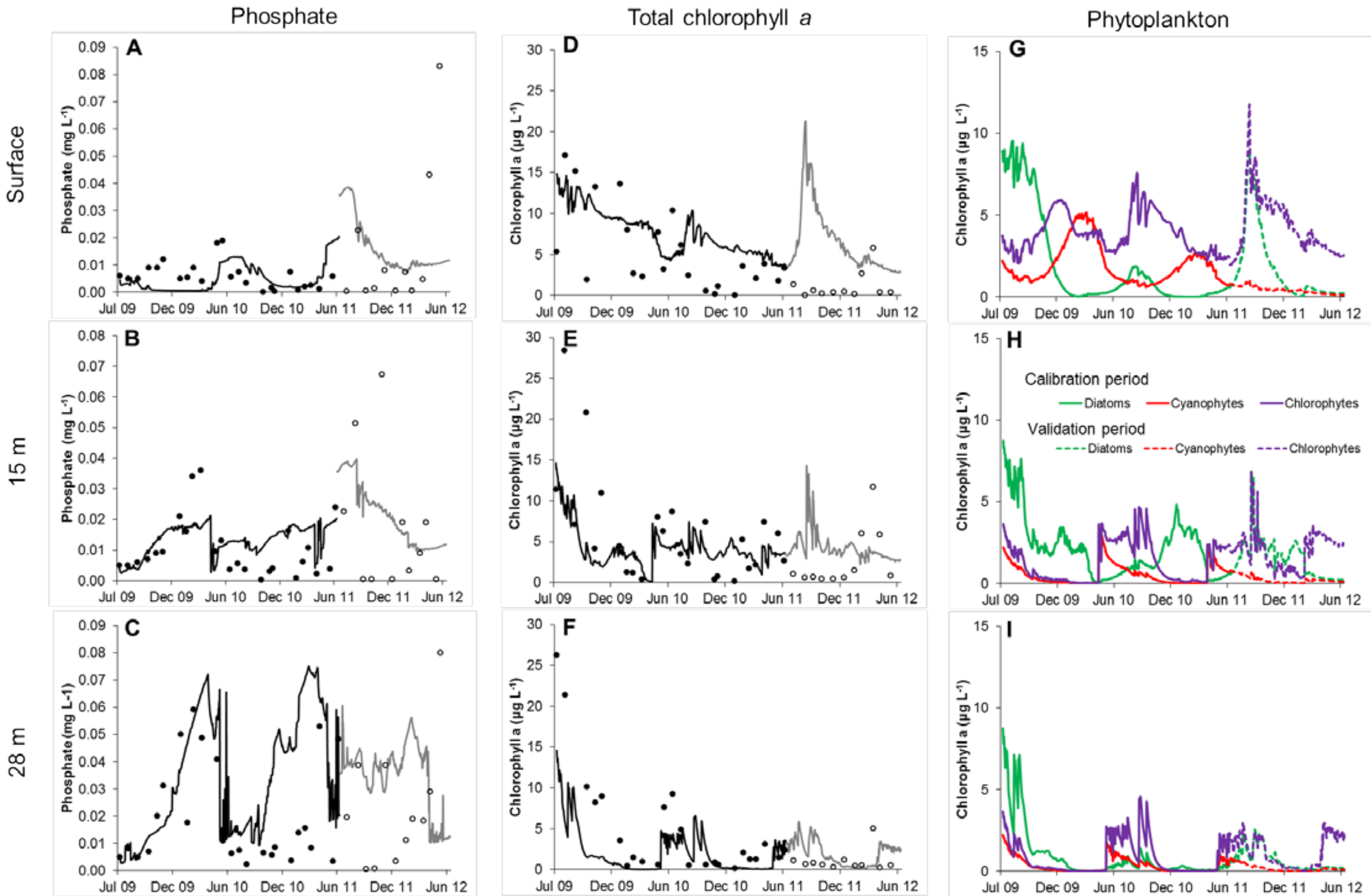

Figure 7: Modelled (DYRESM-CAEDYM) variables (black line = calibration and grey line = validation period) compared with field data (filled circles = calibration and open circles = validation period). A), B) and C) Phosphate (mg L^{-1}) at 0 m, 15 m and 28 m depth, respectively. D), E), and F) Total chlorophyll *a* (µg L^{-1}) at 0 m, 15 m and 28 m depth, respectively. G), H) and I) Phytoplankton groups (NO_3, µg chl *a* L^{-1}) 0 m, 15 m and 28 m depth, respectively. See legend in H) for key to phytoplankton groups.

Table 3: Statistical comparison of DYRESM-CAEDYM model simulations with field data (i.e. monthly measurements at 0 m, 15 m and 28 m depth) in Lake Rotokakahi, using Pearson correlation coefficient (R), mean absolute error (MAE), mean of observations ($Mean_{obs}$), and mean of model values ($Mean_{mod}$), for each variable.

		Calibration period (July 2009 – June 2011)				Validation period (July 2011 – June 2012)			
Variable	Depth (m)	R	MAE	$Mean_{obs}$	$Mean_{mod}$	R	MAE	$Mean_{obs}$	$Mean_{mod}$
Temperature (°C)	0	0.997	0.333	15.268	15.037	0.992	0.352	15.445	15.522
Dissolved oxygen (mg L^{-1})	0	0.497	1.562	7.797	9.022	0.840	0.777	8.777	9.052
Total phosphorus (mg L^{-1})	0	0.197	0.014	0.032	0.039	-0.236	0.031	0.055	0.042
Total nitrogen (mg L^{-1})	0	-0.145	0.112	0.293	0.203	0.273	0.089	0.188	0.175
Total chlorophyll *a* (µg L^{-1})	0	0.504	4.065	5.483	7.654	-0.332	6.334	1.141	7.220
Nitrate (mg N L^{-1})	0	0.386	0.009	0.011	0.002	0.889	0.007	0.013	0.006
Ammonium (mg N L^{-1})	0	0.340	0.021	0.032	0.016	0.164	0.015	0.019	0.014
Phosphate (mg L^{-1})	0	0.124	0.005	0.006	0.005	-0.232	0.019	0.016	0.015
Temperature (°C)	15	0.956	0.377	11.355	11.264	0.910	1.132	12.570	13.518
Dissolved oxygen (mg/L)	15	0.790	1.608	6.608	6.408	0.658	2.163	7.398	7.102
Total phosphorus (mg/L)	15	0.015	0.019	0.031	0.043	-0.548	0.038	0.059	0.045
Total nitrogen (mg/L)	15	-0.341	0.094	0.276	0.215	0.369	0.115	0.263	0.182
Total chlorophyll a (µg/L)	15	0.475	3.782	6.130	4.539	-0.222	3.987	2.713	4.291
Nitrate (mg N/L)	15	-0.103	0.007	0.010	0.005	0.432	0.019	0.021	0.010
Ammonium (mg N/L)	15	0.414	0.028	0.049	0.053	-0.052	0.027	0.039	0.032
Phosphate (mg/L)	15	0.401	0.007	0.010	0.013	0.416	0.016	0.018	0.021
Temperature (°C)	28	0.931	0.333	10.767	10.595	0.890	1.911	10.937	12.801
Dissolved oxygen (mg/L)	28	0.918	1.286	5.652	4.774	0.511	3.407	4.652	3.773
Total phosphorus (mg/L)	28	0.197	0.020	0.053	0.056	-0.012	0.052	0.101	0.054
Total nitrogen (mg/L)	28	-0.010	0.137	0.351	0.307	-0.046	0.177	0.368	0.215
Total chlorophyll a (µg/L)	28	0.851	3.425	4.941	2.329	-0.324	1.628	1.073	1.657
Nitrate (mg N/L)	28	0.306	0.017	0.011	0.014	0.497	0.013	0.010	0.013
Ammonium (mg N/L)	28	0.713	0.072	0.124	0.173	0.403	0.098	0.165	0.091
Phosphate (mg/L)	28	0.498	0.019	0.019	0.033	-0.576	0.029	0.024	0.037

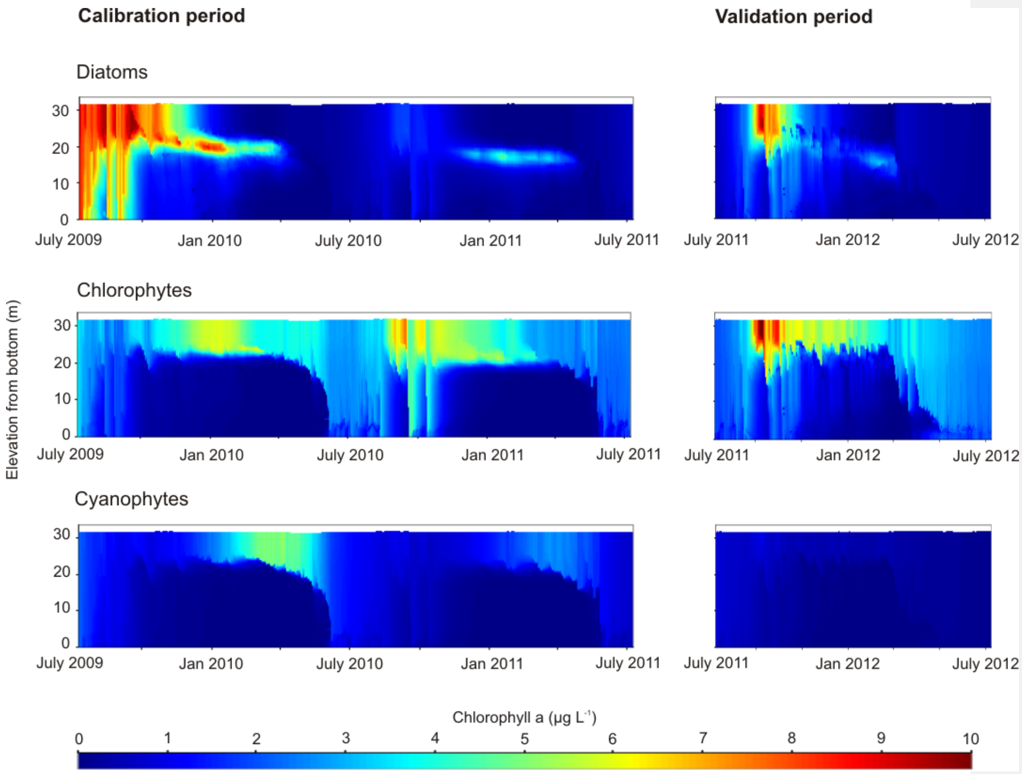

Figure 8: Two-dimensional (time and depth) plots showing modelled (DYRESM-CAEDYM) phytoplankton (diatoms, chlorophytes and cyanophytes) for model calibration period (July 2009 – June 2011) and validation period (July 2011 – June 2012).

3.4 Recommendations

This study has identified a number of data gaps that currently constrain water quality modelling for Lake Rotokakahi. In particular, there was very limited information on the nutrient loads associated with ephemeral and groundwater inflows, and inflow volumes into the lake. For this reason, the current model is unlikely to be particularly useful for modelling scenarios associated with, for example, land use change, or reducing/increasing nutrient loads in lake inflows. It is recommended that further model development and data collection is required before the model may be used as a decision-support tool for lake managers.

The performance of the 1D model described in this report could be improved by collecting data on surface and ephemeral inflow volumes and nutrient concentrations under a range of hydrological conditions, and collecting further samples to quantify groundwater nutrient concentrations. This is in line with recent recommendations made by Butterworth (2012) to include groundwater and ephemeral inflows in the lake monitoring programme. Moreover, as plantation forestry comprises a significant proportion of Lake Rotokakahi's catchment, it would likely be instructive to quantify the impact of harvesting on nutrient and sediment loads in ephemeral inflows located close to harvesting sites, as ephemeral flows over bare ground may mobilise significant amounts of sediment and associated nutrients (Marden 2004).

It is possible that the performance of the DYRESM-CAEDYM model may also be improved by inclusion of zooplankton, which may impact phytoplankton populations at certain times of the year. However, this will require zooplankton sampling at a similar temporal resolution to current lake water quality (e.g. nutrient and chlorophyll *a* concentration) measurements.

The advantage of DYRESM-CAEDYM is that it can easily be used for long-term simulations (i.e. comprising several years) to explore the impact of various chronic stressors (e.g. eutrophication, climate change) or management scenarios on lake water quality. However, Lake Rotokakahi may not be an ideal candidate for a 1D model such as DYRESM-CAEDYM, due to the complex morphometry of the lake basin. Furthermore, DYRESM-CAEDYM is unlikely to be useful for modelling kakahi in this lake. Instead, it may be more suitable to use a 3D coupled hydrodynamic-ecological model, such as ELCOM-CAEDYM, with inclusion of a bivalve group to represent kakahi, to model lake water quality. It should be noted that this will require significant resources to properly calibrate and validate the model, as well as further data on lake inflow volumes and nutrient loads already described above.

The topography around Lake Rotokakahi is such that meteorological data (particularly relating to wind speed and direction) may not be appropriate if sourced from a climate station some distance away (e.g. Rotorua). Model performance (both 1D and 3D applications) would likely be improved by collecting meteorological data on, or very close to, the lake. Alternatively, some effort could be directed at comparing meteorological conditions at Lake Rotokakahi with those at an established climate station. For example, regression models could be developed that relate air temperature, wind speed and direction collected at a permanent climate station with spot measurements of those same variables over the lake.

Recent monitoring data indicate that total phosphorus and phosphate concentrations have increased in both the surface inflow and in the lake over the period July 2012 to April 2013 (Figure 9). Phosphate concentration in the surface inflow increased from < 0.1 mg L^{-1} between July 2009 and July 2012 to c. 0.2 mg L^{-1} from August 2012 to April 2013. In the lake, phosphate concentration also increased substantially, from < 0.02 mg L^{-1} prior to July 2012 to > 0.12 mg L^{-1} in 2013. There was no concurrent increase in total nitrogen, nitrate or ammonium evident in field data for either the surface inflow or the lake. The reasons for this increasing trend in phosphorus concentration in the inflow and the lake are unclear, but it is alarming given the potential for nitrogen-fixing cyanobacteria species such as *Anabaena* spp. to bloom when phosphate concentrations are high. The lake previously experienced a bloom of *Anabaena lemmermannii* in May 2011, which may have resulted in a fish kill in the lake outlet stream, and it is important that the cause of the recent increase in phosphorus concentrations is investigated further.

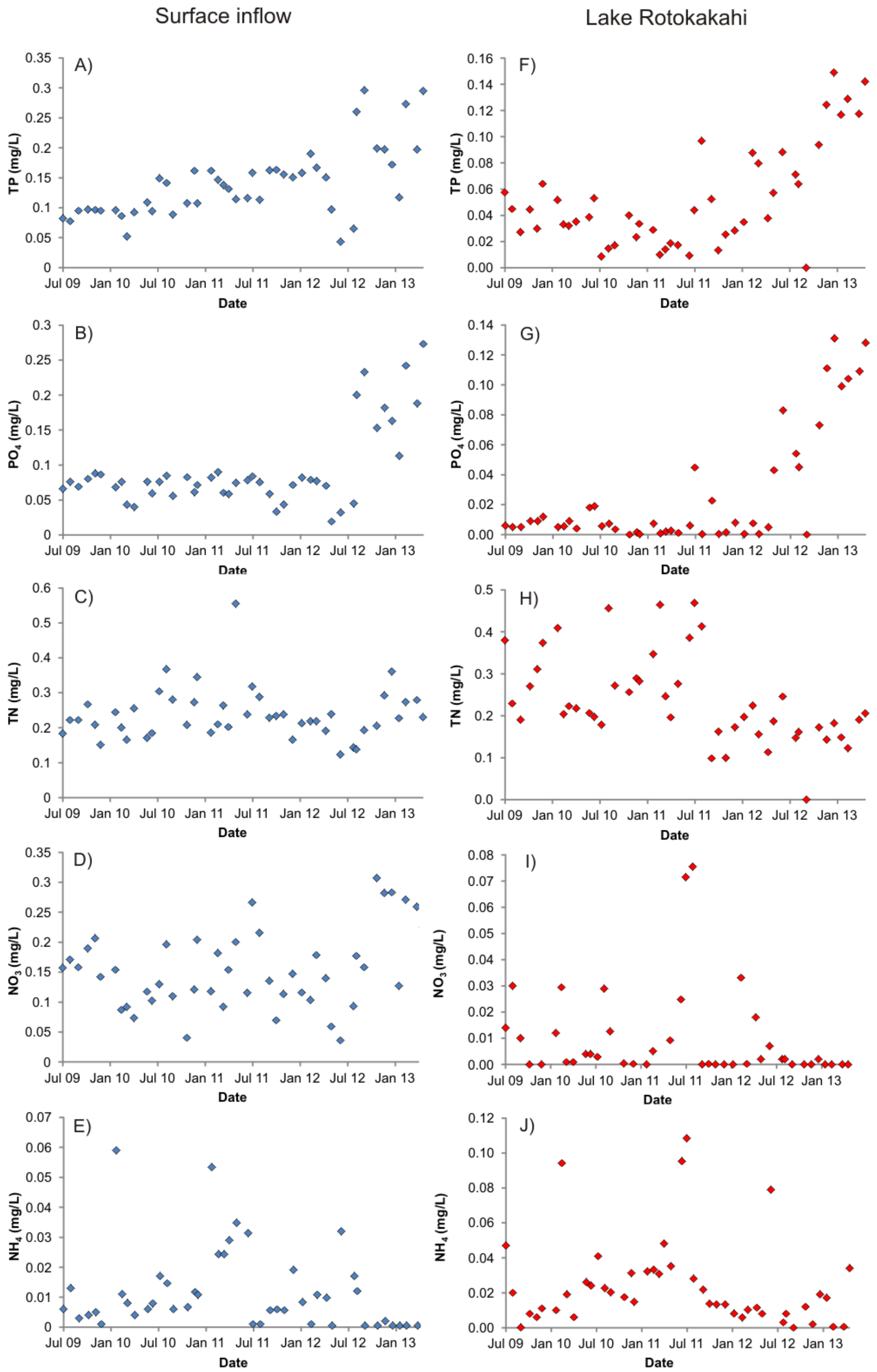

Figure 9: Total phosphorus (TP; mg/L), phosphate (PO_4; mg/L), total nitrogen (TN; mg/L), nitrate (NO_3; mg N/L) and ammonium (NH_4; mg N/L) concentration in the surface inflow (left panel) and Lake Rotokakahi surface measurements (right panel) from July 2009 to April 2013.

4 Conclusions

In this study we have developed a DYRESM-CAEDYM model for Lake Rotokakahi, and estimated inflow volumes and nutrient loads to the lake using a catchment water balance. Model performance statistics indicated reasonable simulation of water quality for the calibration period, but did not satisfactorily capture the magnitude and dynamics of chlorophyll *a* and some nutrient species over an independent model validation period. There may be a number of reasons for the poor model performance over the validation period. For example, it may be that zooplankton and/or kakahi, which were not included in the model configuration, may exert significant grazing pressure on the phytoplankton populations at certain times, and this cannot be compensated for by assuming a constant value for phytoplankton mortality. Furthermore, there was significant uncertainty in the catchment water and nutrient loads as nutrient concentrations are only routinely monitored in the one permanent surface inflow to the lake. As ephemeral streams and groundwater very likely comprise a substantial component of inflow volume and nutrient loads, the very limited data to parameterise these components most likely will have affected model performance. The further complication of large areas of forestry that may have contributed to variability in discharge, sediment and nutrients during the study period reinforces some current limitations in the use of the lake model to be able to be used in a scenario testing context.

In its current form, given the unsatisfactory performance during the model validation period and uncertainty in model forcing data, the DYRESM-CAEDYM model is not suitable for scenario testing of lake management options. It is recommended that effort is directed at quantification of ephemeral and groundwater inflows and their associated nutrient and (particularly for ephemeral inflows) sediment loads. This may be particularly important for ephemeral inflows located close to the lake that may be influenced by forestry harvesting operations. Recent increases in measured total phosphorus and phosphate concentrations in the surface inflow and in the lake, combined with the degradation of water quality that has already occurred over the last 20 years, provides further impetus for addressing this critical information gap. Were new data to become available, opportunities exist for improving the performance of the current model and for developing a three-dimensional coupled hydrodynamic-water quality model (e.g. ELCOM-CAEDYM) with representation of kakahi and/or zooplankton, which may be able to resolve questions pertinent to the functioning of the lake, and to lake and catchment management.

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Appendix A: DYRESM-CAEDYM parameters

Table A1: Parameters used in DYRESM for Lake Rotokakahi

Parameter	Value	Unit
Critical wind speed	3.0	$m\ s^{-1}$
Emissivity of water surface	0.96	-
Mean albedo of water	0.08	-
Potential energy mixing efficiency	0.2	-
Shear production efficiency	0.06	-
Vertical mixing coefficient	250	-
Wind stirring efficiency	0.4	-
Effective surface area coefficient	6.0×10^{6}	m^{-2}

Table A2: Light parameters used in CAEDYM for Lake Rotokakahi

Parameter	Description	Value	Units
Extinction coefficients			
KdNIR	Near infrared extinction coefficient	1	m^{-1}
BaseKd	PAR extinction coefficient	0.2	m^{-1}
KdUVA	Ultra Violet A extinction coefficient	1.5	m^{-1}
KdUVB	Ultra Violet B extinction coefficient	2.5	m^{-1}
Fraction of incident short wave radiation			
%NIR	NIR fraction of short wave radiation	0.510	
%PAR	PAR fraction of short wave radiation	0.450	
%UVA	UVA fraction of short wave radiation	0.035	
%UVB	UVB fraction of short wave radiation	0.005	

Table A3: Sediment parameters used in CAEDYM for Lake Rotokakahi

Parameter	Description	Value	Units
Static sediment constants			
vSed	Temperature multiplier of sediment fluxes	1.07	
Sediment oxygen demand			
rSOs	Static sediment exchange rate	2.5	$g\ m^{-2}\ day^{-1}$
KSOs	Half sat constant for DO sediment flux	2.0	$mg\ L^{-1}$
Nutrient fluxes			
SmpPO4	Release rate of PO_4	0.0017	$g\ m^{-2}\ day^{-1}$
KOxS-PO4	Half sat constant for PO_4 sediment flux	5.0	$mg\ L^{-1}$
SmpNH4	Release rate of NH_4	0.0300	$g\ m^{-2}\ day^{-1}$
KDOS-NH4	Half sat constant for NH_4 sediment flux	2.5	$mg\ L^{-1}$
SmpNO3	Release rate of NO_3	-0.1200	$g\ m^{-2}\ day^{-1}$
KDOS-NO3	Half sat constant for NO_3 sediment flux	8.0	$mg\ L^{-1}$
SmpSi	Release rate of Si	0.0800	$g\ m^{-2}\ day^{-1}$
KDOS-Si	Half sat constant for Si sediment flux	8.0	$mg\ L^{-1}$

Table A4: Nutrient cycling parameters used in CAEDYM for Lake Rotokakahi

Parameter	Description	Value	Units
Organic particles (POM)			
POC1max	Max transfer of POCL-DOCL	0.005	day^{-1}
POP1max	Max transfer of POPL-DOPL	0.010	day^{-1}
PON1max	Max transfer of PONL-DONL	0.040	day^{-1}
POMDia1	Diameter of POM particles (labile)	3	µm
POMDensity1	Density of POM particles (labile)	1050	$kg\ m^{-3}$
KePOC1	Specific attenuation coefficient of POM (labile)	0.01	$mg\ L^{-1}\ m^{-1}$
Dissolved organics			
DOC1max	Max mineralisation of DOCL-DIC	0.001	day^{-1}
DOD1max	Max mineralisation of DOPL-PO_4	0.050	day^{-1}
DON1max	Max mineralisation of DONL-NH_4	0.040	day^{-1}
KeDOC1	Specific attenuation coefficient of DOC (labile)	0.01	$mg\ L^{-1}\ m^{-1}$
Dissolved inorganics			
vN2	Temperature multiplier for denitrification	1.07	
KoN2	Denitrification rate coefficient	0.15	day^{-1}
KN2	Half sat constant for denitrification	3.00	$mg\ L^{-1}$
vON	Temperature multiplier for nitrification	1.07	
KoNH	Nitrification rate coefficient	0.05	day^{-1}
KON	Half sat constant for nitrification	2.00	$mg\ L^{-1}$
YNH	Ratio of O_2 to N for nitrification	3.4286	mg N $(mg\ O)^{-1}$

Table A5: Phytoplankton parameters used in CAEDYM for Lake Rotokakahi (cyanophytes, chlorophytes, diatoms)

Parameter	Description	Value	Units
Pmax	Maximum growth rate	0.55,0.9, 1.0	day^{-1}
Ycc	Ratio of C to chl *a*	40, 50, 50	mg C (mg chl *a*)$^{-1}$
IK	Parameter for initial slope of P/I curve	200, 75, 20	µmol $m^{-2}\ s^{-1}$
Kep	Specific attenuation coefficient of phytoplankton	0.025, 0.020, 0.020	µg chl a $L^{-1}\ m^{-1}$
Nutrient parameters			
KP	Half saturation constant for phosphorus	0.0042, 0.0091, 0.0105	$mg\ L^{-1}$
KN	Half saturation constant for nitrogen	0.0294, 0.0630, 0.0735	$mg\ L^{-1}$
KSi	Half saturation constant for silica	0.20 (diatoms only)	$mg\ L^{-1}$
UNmax	Maximum rate of phytoplankton nitrogen uptake	2.56, 5.76, 6.40	mg N (mg chl *a*)$^{-1}$ day^{-1}
UPmax	Maximum rate of phytoplankton phosphorus uptake	0.36, 0.8, 0.84	mg P (mg chl *a*)$^{-1}$ day^{-1}
INmin	Minimum internal nitrogen concentration	3.96 3.30, 3.96	mg N (mg chl *a*)$^{-1}$
INmax	Maximum internal nitrogen concentration	6.60, 7.92, 5.94	mg N (mg chl *a*)$^{-1}$
IPmin	Minimum internal phosphorus concentration	0.25, 0.25, 0.25	mg P (mg chl *a*)$^{-1}$
IPmax	Maximum internal phosphorus concentration	1.13, 0.88, 0.88	mg P (mg chl *a*)$^{-1}$
Temperature limitation			
vT	Temperature multiplier for phytoplankton growth	1.07, 1.07, 1.07	
Tsta	Standard temperature	20, 18, 16	º C
Topt	Optimum temperature	28, 25, 23	º C
Tmax	Maximum temperature	38, 38, 35	º C
Respiration, mortality and excretion			
kr	Respiration rate coefficient	0.065, 0.110, 0.120	day^{-1}
vR	Temperature multiplier for phytoplankton respiration	1.07, 1.07, 1.07	
fres	Fraction of respiration relative to total	0.8, 0.8, 0.8	

	metabolic loss rate		
fdom	Fraction of metabolic loss rate that goes to DOM	0.3, 0.3, 0.3	
Settling			
ws	Constant settling velocity	0.00E+0, -0.85E-7, -0.10E-5	m s^{-1}