A water quality model for Lake Tikitapu

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Executive Summary

Lake Tikitapu is a small lake in the Rotorua Te Arawa Lakes region which is extensively used for recreation and sporting events, and is of cultural significance to Iwi (Te Arawa). It is an attractive and popular lake with oligotrophic-mesotrophic water quality. Tikitapu's target Trophic Level Index (TLI; Burns 1999) is 2.7, whereas a TLI of approximately 3 was observed between 2000 and 2010. An Action Plan has been established for Lake Tikitapu (BoPRC 2011) and the proposed actions have now been completed (as at 2015), including the reticulation of the lakeside wastewater systems.

This report describes the establishment of a one-dimensional hydrodynamic-ecological computer water quality model (DYRESM-CAEDYM) for Lake Tikitapu. The modelling process includes calculations for catchment and lake water balances, as well as estimation of nutrient loads to the lake. The simulation period spans from 2001 to 2010. The model has been calibrated and validated, and model performance is acceptable relative to other DYRESM-CAEDYM lake applications documented in the literature.

The established model can be used for simulating scenarios of lake management actions, and can be considered a 'decision support tool'. Initial simulations are presented for increased diffusion of silica from lake sediments (C. Hendy, *pers. comm.*), and for reticulation of lakeside wastewater systems. Septic systems comprise a large fraction of estimated annual nutrient loads, particularly for phosphorus. As such, simulation of the removal of septic tank nutrient loads indicated that this action alone may be sufficient to meet the TLI target for the lake.

Acknowledgements

We thank Paul Scholes (Bay of Plenty Regional Council) for providing field observation data. We also thank Chris Hendy for supplying student field trip data for groundwater chemistry, as well as observations regarding internal diffusion of silica from lake sediments. The DYRESM-CAEDYM models were developed at the Centre for Water Research, University of Western Australia, and are used by The University of Waikato under license.

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1 Introduction

Lake Tikitapu is a small lake of cultural significance in the Rotorua region, which is extensively used for recreation and sporting events. It is a popular lake of oligotrophic-mesotrophic productivity. Water quality in the Te Arawa lakes is usually reported using the Trophic Level Index (TLI; Burns 1999), an index of annual average water quality. Each lake in the region has a 'TLI target' value consistent with water quality prior to land use intensification and/or commensurate with community aspirations for the lake. Titkitapu's target TLI is 2.7 (with values between 2 and 3 indicating oligotrophic water quality), however, a TLI of approximately 3 (the threshold for mesotrophic water quality) was observed between 2000 and 2010. Primary production in the lake is strongly dominated by chlorophytes (Figure 2), due to relatively low concentrations of silica in the lake, thus limiting production by diatoms (McColl 1972, Ryan 2006).

Lake Tikitapu is co-managed by the Bay of Plenty Regional Council (BoPRC), Te Arawa Lakes Trust, and Rotorua District Council. Recent initiatives have sought to address potential causes of elevated TLI including, but not limited to, the reticulation of sewerage systems within the lake catchment. In June 2011, BoPRC released an action plan for Lake Tikitapu, outlining present and future management actions and calling for adaptive management and rigorous environmental monitoring (BoPRC, 2011).

Decision support tools available to assist lake managers include computer lake ecosystem models, which can be used to simulate current lake conditions and assess the potential impact of changes to boundary conditions such as climate, land use and/or inflows. This report describes the setup of the one-dimensional (1D) hydrodynamic-ecological model DYRESM-CAEDYM for Lake Tikitapu, as well as the application of a management scenario whereby the nutrient load to the lake from septic tanks is removed. A further scenario of increased silica diffusion from lake sediments is also simulated. While this report is intended as a guide to the model setup and application, the model may be used in future to simulate other lake management scenarios.

2 Methods

2.1 Study site

Lake Tikitapu is a relatively small (144 ha) but deep (27.5 m) lake in the mid-west of the Rotorua Lakes region at 415 m above sea level (Figure 1). It was formed approximately 13500 years ago, and has a 430 ha, predominantly forested catchment (Table 1). The lake has no persistent surface water inflow or outflow, however, water is presumed to enter the lake via groundwater inputs, and drain to adjacent Lake Rotokakahi via groundwater (BoPRC 2011).

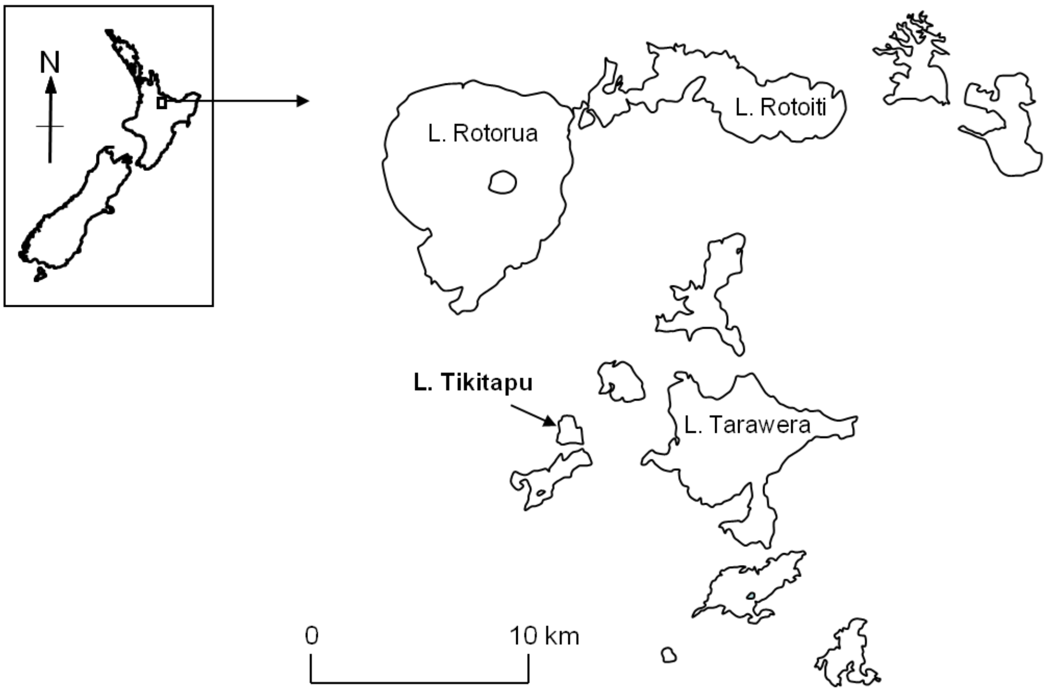

Figure 1: Location of Lake Tikitapu, in the Rotorua Lakes district.

2.2 Model description of DYRESM-CAEDYM

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 and used under license from the Centre for Water Research, The University of Western Australia. DYRESM resolves the vertical distribution of temperature, salinity, and density in lakes and reservoirs, while CAEDYM simulates time varying fluxes of biogeochemical variables (e.g., nutrient species, phytoplankton biomass). The model includes comprehensive process representations for carbon (C), nitrogen (N), phosphorus (P), and dissolved oxygen (DO) cycles, and several size classes of inorganic suspended solids. Several applications have been made of DYRESM-CAEDYM to different lakes (e.g., Bruce et al., 2006; Burger et al., 2008; Trolle et al., 2008; Gal et al., 2009) and these applications are associated with detailed descriptions of the model equations.

The variables in CAEDYM may be configured according to the goals of the model application and availability of data. For example, it is possible to simulate up to seven different phytoplankton groups, five zooplankton groups, fish, and macrophytes. The interactions between phytoplankton growth and losses, sediment nutrient fluxes, and the mineralisation and decomposition of particulate organic matter influence N and P cycling in the model (Figure 3). Fluxes of dissolved inorganic and organic nutrients from the bottom sediments are dependent on the temperature, NO_3-N and DO concentration in the water layer immediately above the sediment surface, with calibration of parameters specific to each application.

2.3 DYRESM-CAEDYM configuration

Monitoring data from Lake Tikitapu (The University of Waikato, unpubl.) show strong dominance of chlorophytes, with occasional populations of diatoms, and negligible presence of other taxa (Figure 2). Therefore, in this study only chlorophytes and diatoms were simulated in CAEDYM. Because silica concentrations in Lake Tikitapu are low (McColl 1972, BoPRC, unpubl.), SiO_2 was also simulated to account for silica limitation of diatom growth. No higher biology or macrophytes were included in the application of CAEDYM, rather, grazing effects were accounted for by slightly elevated coefficients of phytoplankton respiration and mortality.

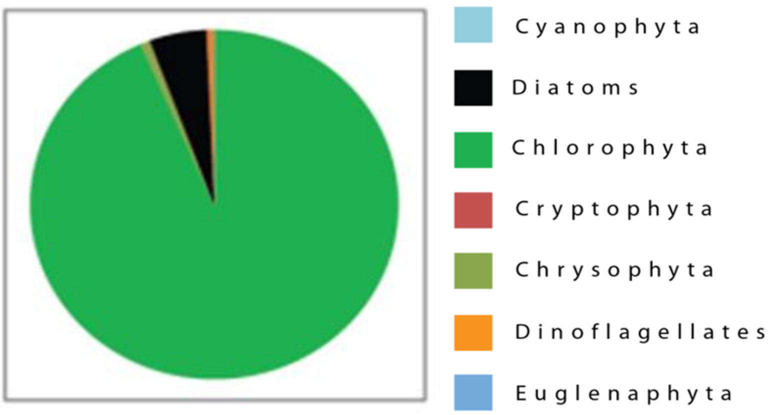

Figure 2. Mean proportion of algal taxa (2007 to 2011) in Lake Tikitapu (data from BoPRC; figure by W. Paul, unpubl.).

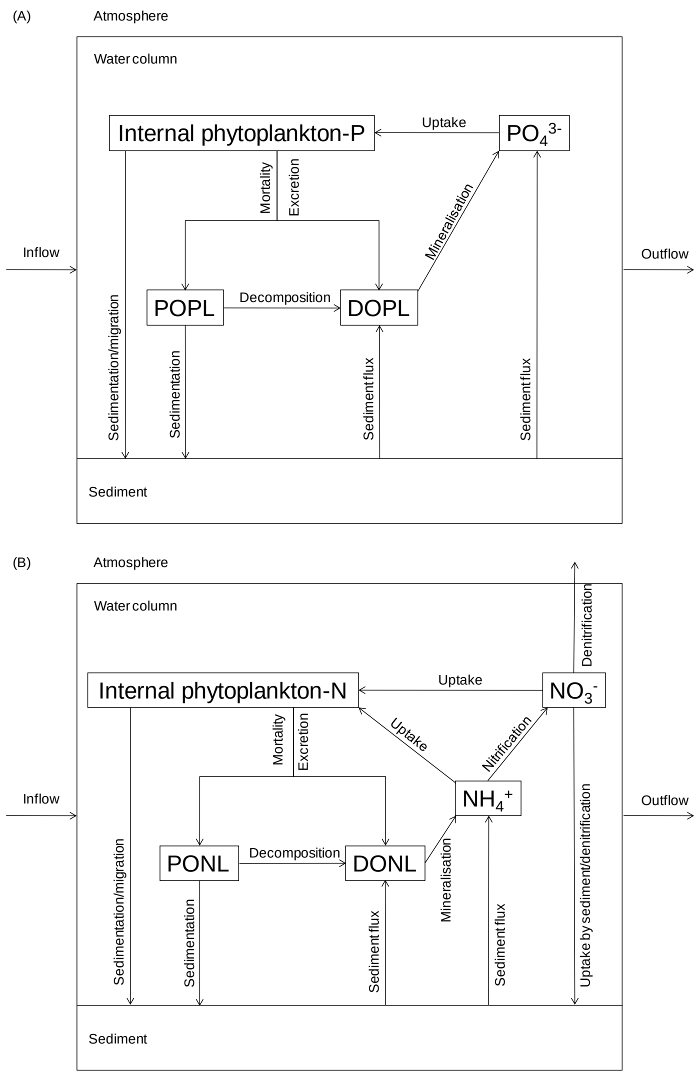

Figure 3: Conceptual model of the (A) phosphorus and (B) nitrogen cycles represented in DYRESM-CAEDYM for the present study. POPL, PONL, DOPL and DONL represent particulate labile organic phosphorus and nitrogen, and dissolved labile organic phosphorus and nitrogen, respectively.

2.4 Bathymetry

Lake Tikitapu has simple bathymetry, catchment topology and hydrology, making it an excellent candidate for a one-dimensional (vertically resolved) model such as DYRESM. Hypsographic data (Figure 2) for Lake Tikitapu were obtained from Bay of Plenty Regional Council.

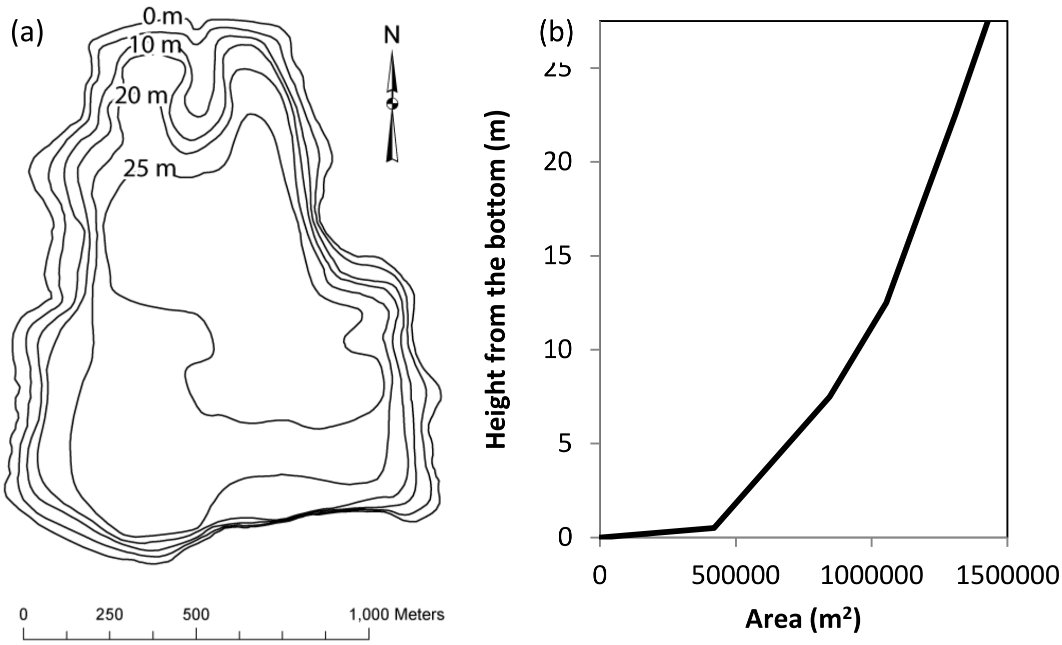

Figure 4: Plot of a) Depth contour map and b) depth vs volume for Lake Tikitapu.

2.5 Meteorological input

Meteorological data for previous model applications in the Rotorua lakes were obtained from Rotorua Airport climate station, located about 50 m from the Lake Rotorua shoreline. Although Lake Tikitapu is approximately 8.5 km away from the Rotorua Airport, this station is the nearest that provides a continuous record of daily values for all required input variables.

Data are collected at Rotorua airport hourly, and for the purposes of model input were aggregated as daily average values except for rainfall, which were daily totals.

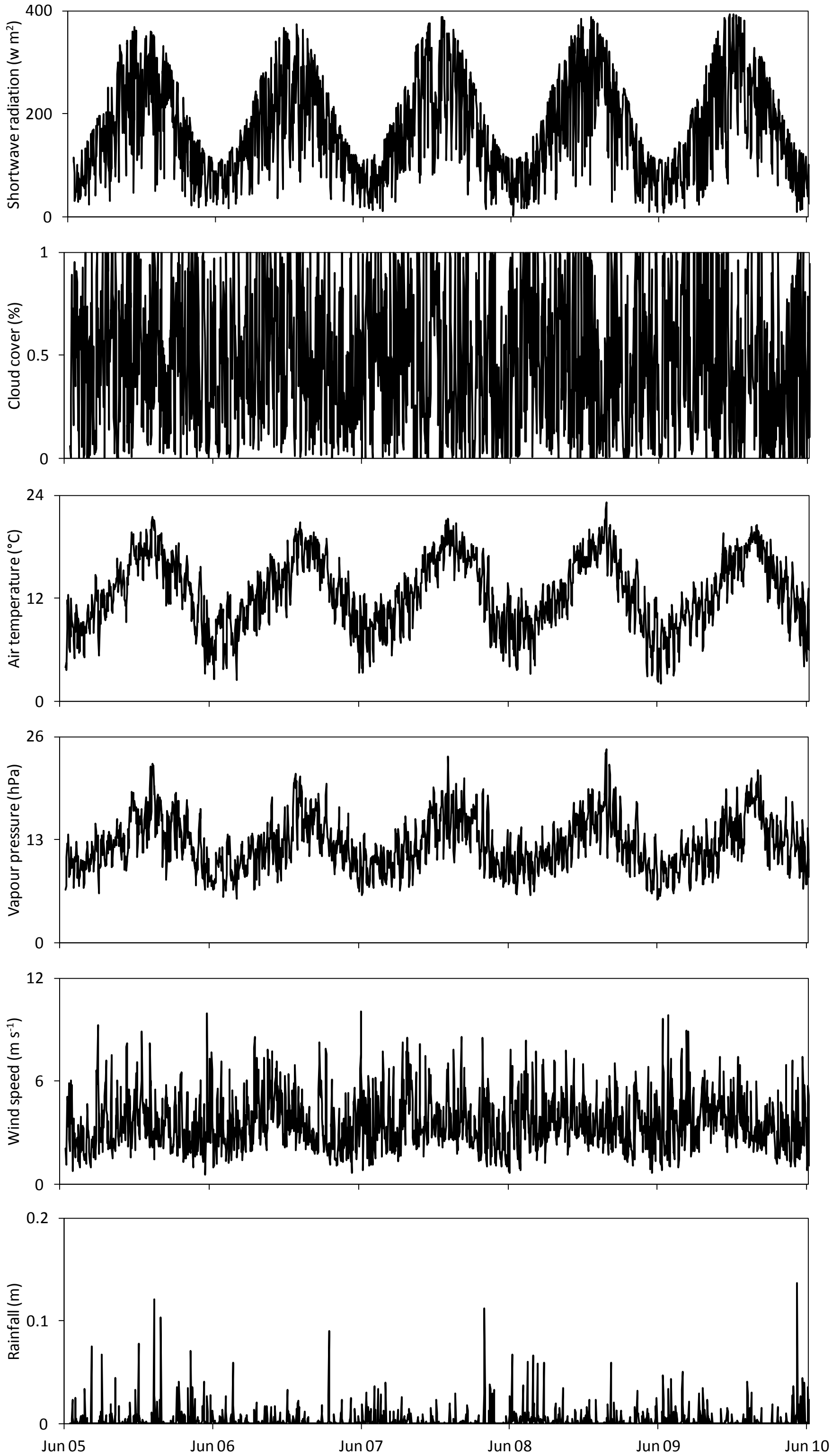

Figure 5: Meteorological data used as input to the DYRESM model for the model calibration period (July 2005 – June 2010).

2.6 Lake water balance

A water balance was calculated for Lake Tikitapu using all hydrological data available for the lake and catchment over the simulation period, such that:

$$\Delta S = \sum(surface\ inflows) + groundwater + rainfall - E_L - Outflow \quad (1)$$

where:
E_L is evaporation in $m^3\ d^{-1}$
ΔS is change in storage in $m^3\ d^{-1}$

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, and a 30-day running average was used to smooth the step changes between measurements (Figure 7a).

Evaporation from the lake (Figure 7b) 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) using meteorological input data and water temperature:

$$Q_{lh} = minimum\left(0 \geq \frac{0.622}{P} C_L \rho_A C_E U_A (e_A - e_A(T_S))\Delta t\right) \quad (2)$$

where:
Q_{lh} is evaporative heat flux in $J\ m^{-2}\ s^{-1}$
P is atmospheric pressure in hPa
C_L is latent heat transfer coefficient for wind speed at a height of 10 m (1.3×10^{-3})
ρ_A is density of air in $kg\ m^{-3}$
L_E is latent heat evaporation of water (2.453×10^6) in $J\ kg^{-1}$
U_A is wind speed in at 10 m height above ground level in $m\ s^{-1}$
$e_A(T_s)$ saturation vapour pressure at the water surface temperature in hPa
e_A is vapour pressure of air in hPa

The condition that $Q_{lh} \leq 0$ excludes for condensation effects.

For the purpose of estimating water evaporated from the lake surface (Figure 7B), surface water temperature was estimated from an empirical relationship between lake surface temperature and 3-day averaged air temperature (Figure 6). The saturated vapour pressure $e_s(T_s)$ is calculated via the Magnus-Tetens formula (TVA 1972, eqn. 4.1):

$$e_s(T_S) = exp\left(2.3026\left(\frac{7.5T_S}{T_S+237.3} + 0.7858\right)\right) \quad (3)$$

where:
T_s is the water surface temperature in °C

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

$$\Delta M_N^{lh} = \frac{-Q_{lh}A_N}{L_V} \quad (4)$$

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

ΔM_N^{lh} was multiplied by 86.4 to give daily evaporation (E_L) in m^3 d^{-1}.

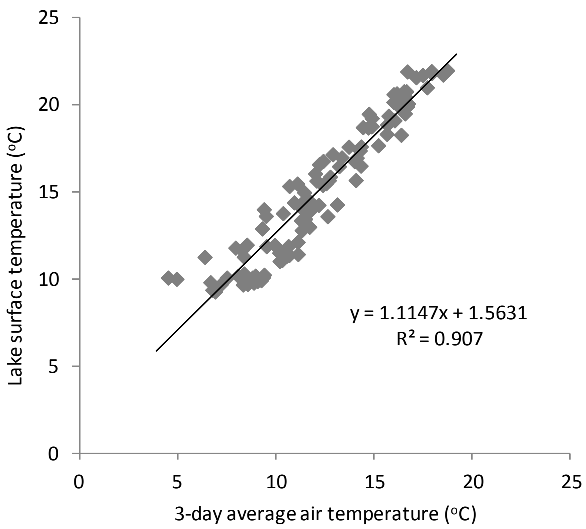

Figure 6. Observed air temperature at Rotorua airport and lake surface water temperature at Lake Tikitapu.

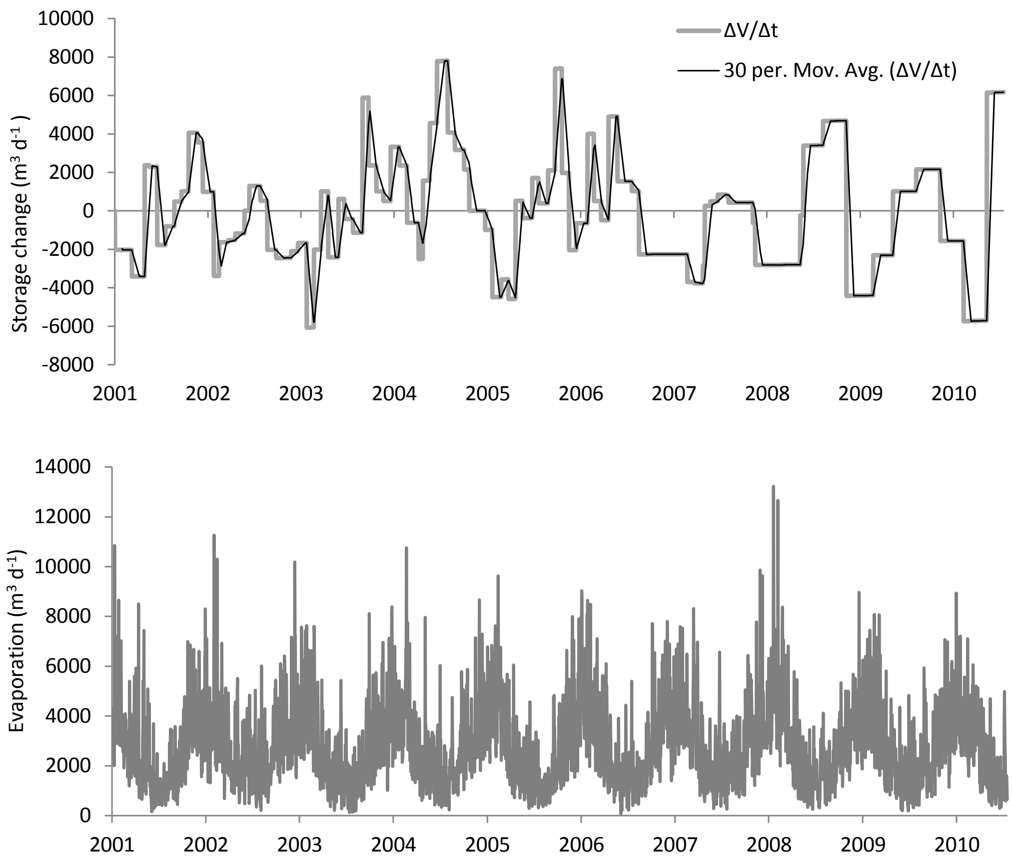

Figure 7. A) Periodically-measured and 30-day running average lake storage change, and B) estimated daily evaporation from Lake Tikitapu.

2.7 Catchment water balance

In order to estimate inflows to the lake, a catchment water balance was undertaken. Catchment land type data were obtained from BoPRC via a land use GIS layer. The catchment was divided into two sub-sections, 'Overflow' (24.5 ha, predominantly campground adjacent to the lake) and residual (predominantly forested) catchment (Table 1).

Table 1. Catchment land types within the two sub-catchments used for the Lake Tikitapu DYRESM CAEDYM model.

CATCHMENT TYPE	Area (ha)
Bare ground	1.7
Grassland	9.1
Lake reeds	1.1
Urban built	12.2
Urban grassland	0.5
Overflow catchment SUBTOTAL	**24.5**
Exotic forest	60.0
Indigenous forest	344.0
Scrub	1.5
Main catchment SUBTOTAL	**405.5**
TOTAL	***430.0***

2.7.1 Surface inflows ('overflow')

Lake Tikitapu does not receive any persistent surface inflows. However, storm water surface runoff from the campground beside the lake has been observed during storm events (J. McIntosh, *pers. comm.*). For the purpose of the water balance, total daily rainfall > 15 mm was defined as a storm event, during which 30 % of rainfall to the urban-pasture catchment was directed to the lake as surface inflow.

2.7.2 Rainfall

In order to include aerial deposition of nitrogen and phosphorus within the ecological component of the model, measurements of rainfall were set to zero within the DYRESM meteorology (*.met) file and instead included within the inflows (*.inf) file by multiplying the water level-dependent lake surface area (m^2) and rainfall (m).

2.7.3 Groundwater inflow

Inflowing water other than storm surface runoff or rainfall was represented as a single groundwater inflow from the catchment, and derived from a catchment water balance. Catchment evapotranspiration rates were assumed to be similar to those presented in Scotter and Kelliher (2004) – 800 mm yr^{-1} for pasture and 1000 mm yr^{-1} for forestry, from an average annual rainfall of 1850 mm yr^{-1}. Based on these figures, land use-weighted average catchment evapotranspiration rate was calculated as 53.4 % of rainfall. Seasonal variation in evapotranspiration was approximated by applying a seasonal sinusoidal pattern about a mean of 53.4 %, with a peak of 73.4 % during summer and minimum of 33.4 % during winter (Figure 8a). Mean annual volume of the modelled groundwater inflow was 2664512 m^3 yr^{-1} (Figure 8b).

2.7.4 Septic tank inflow

Septic tank discharge volume was derived from annual nitrogen and phosphorus loads of 700 and 70 kg yr^{-1} respectively, as presented in McIntosh (2010). Nitrogen and phosphorus from septic tank leachate were represented as nitrate and phosphate concentrations of 70 and 7 g m^{-3} respectively, based on previous model applications which included septic tanks. This yielded a mean daily discharge of 27.4 m^3 day^{-1} from septic tanks within the catchment. A sinusoidal pattern of discharge volume was applied to the septic tank discharge in order to represent increased usage of public and campground facilities during summer, giving a summer maximum of 37.4 m^3 day^{-1} and winter minimum of 17.4 m^3 day^{-1}.

2.7.5 Outflow

Outflow from Lake Tikitapu (Figure 8C) was derived using Equation 1 with measured rainfall and storage change, and estimated lake inflow and evaporation (Figure 8c).

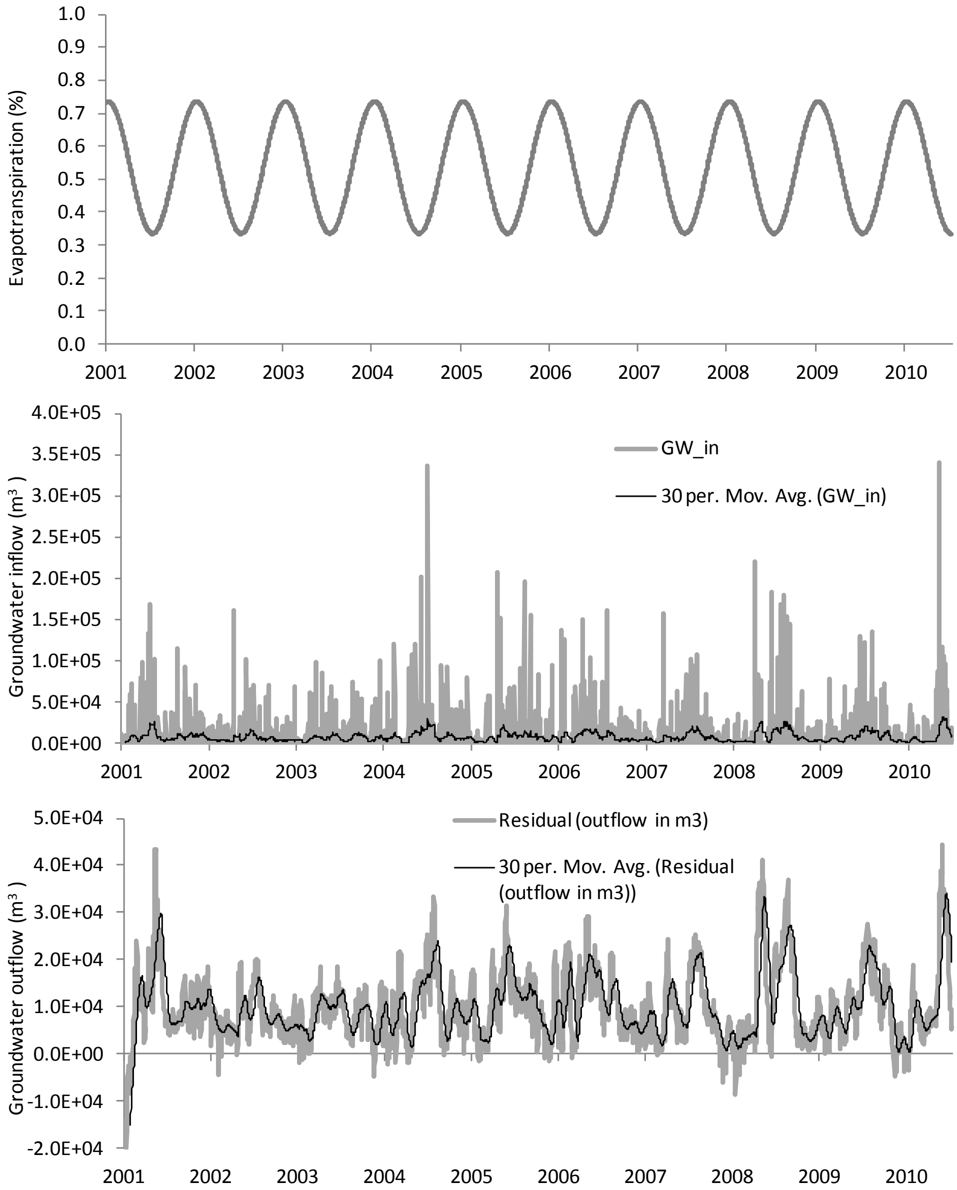

Figure 8. A) Modelled seasonal fraction of precipitation lost as evapotranspiration, B) estimated groundwater inflow to Lake Tikitapu derived from the catchment water balance with 30-day running average, and C) modelled groundwater outflow from Lake Tikitapu. 30-day running averages were used to smooth peak volume and avoid occurrences of negative flows.

2.8 Inflow parameterization

2.8.1 Temperature

The temperature of surface runoff, rainfall and septic tank inflows were set equal to estimated lake surface temperature, which was derived by linear correlation of air and water temperature measurements (Figure 6), yielding the relationship:

$$T_s = 1.1092 * T_{air} + 1.625 \qquad (5)$$

where:

T_s is derived water temperature in ^oC

T_{air} is measured air temperature in ^oC

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

$$T_s = A\cos(\omega t + \sigma) + T_0 \qquad (6)$$

where:

T_s is derived water temperature in ^oC
A is amplitude in m
ω is angular frequency (2π/365)
σ is phase angle
T_0 is mean water temperature, 11^oC
t is time in days

2.8.2 Dissolved oxygen

Dissolved oxygen concentrations of inflows were estimated as a function of water temperature (Mortimer 1981) based on data from Benson and Krause (1980):

$$DO = exp(7.71 - 1.31ln(T + 45.93)) \qquad (7)$$

where:

DO is dissolved oxygen in mg L^{-1}
T is water temperature in $^{\circ}C$

Dissolved oxygen concentration in the groundwater and septic tank inflows were reduced by 20%.

2.8.3 Nutrients

Catchment loads of total phosphorus and total nitrogen loads of 2502 kg N y^{-1} and 125 kg P y^{-1} have been estimated previously using approximate aerial discharge rates and catchment land use (McIntosh 2010; Figure 9).

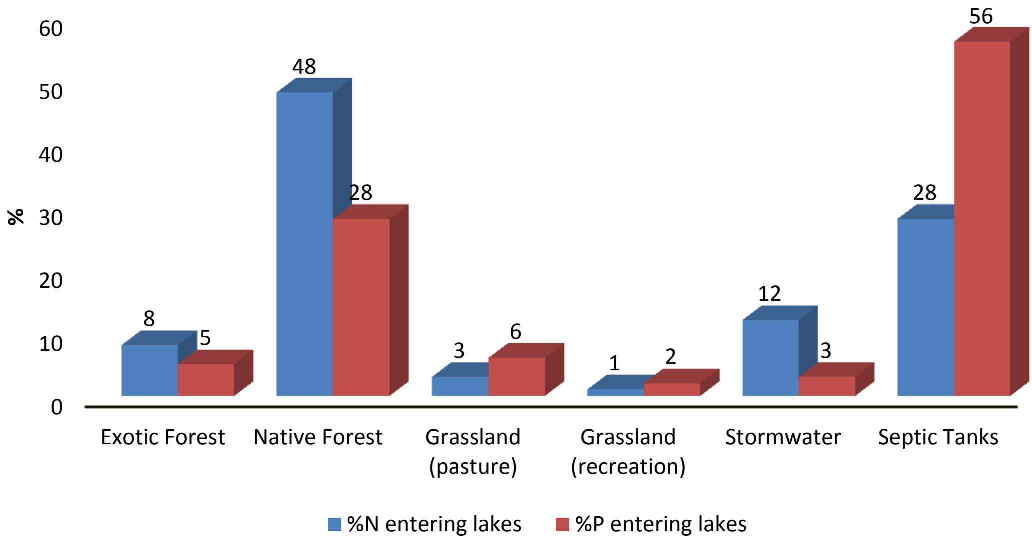

Figure 9. Estimated nutrient loads to Lake Tikitapu. Taken from McIntosh (2010), as presented in BoPRC (2011).

Relatively few empirical data are available for groundwater inflow nutrient concentrations in the Tikitapu catchment. Groundwater nutrient concentrations were analysed as part of a University of Waikato undergraduate fieldtrip in 2011 (Table 2). For the current model application, groundwater was assigned constant nutrient concentrations equal to the mean of all sites surveyed, and was assumed to be void of any particulate organic nutrients (PONL and POPL).

Table 2. Groundwater nutrient measurements from University of Waikato field trip, 2011.

Location	NH_4-N ($g\ m^{-3}$)	NO_2-N ($g\ m^{-3}$)	NO_x-N ($g\ m^{-3}$)	NO_3-N ($g\ m^{-3}$)	TP ($g\ m^{-3}$)	DOPL ($g\ m^{-3}$)	Si ($g\ m^{-3}$)
Okareka loop road 1	0.568	0.002	0.096	0.095			8.960
Okareka loop road 2	0.137	0.005	0.104	0.099	0.002	0.002	14.645
Okareka loop road 3	0.152	0.005	0.112	0.107	0.001	0.001	14.913
Beach beside forest 1	0.107	0.003	0.112	0.109	0.002	0.000	14.077
Beach beside forest 2	0.317	0.002	0.102	0.100	0.005	0.000	12.439
Walking track 1	0.131	0.001	0.099	0.098	0.001	0.001	8.103
Walking track 2	0.100	0.001	0.099	0.098	0.004	0.000	12.378
Walking track 3	0.849	0.038	0.147	0.109	0.001	0.001	3.349
Mean	**0.295**	**0.007**	**0.109**	**0.102**	**0.002**	**0.001**	**11.108**

In the absence of empirical measurements, surface runoff inflow was assumed to have three times the nutrient concentrations of groundwater inputs. Additionally, surface inflows were assigned particulate organic nutrients (PONL and DONL) equal to the assumed values for dissolved organic nutrients (DONL and PONL).

Rainfall nutrient concentrations were estimated using available values for aerial deposition rates in the literature. The mean of values presented in Hamilton (2005) and Parfitt et al. (2006) yielded nitrate and phosphate concentrations of 0.19 and 0.014 respectively. Rainfall was assumed to be void of ammonium and organic forms of nitrogen or phosphorus. Nitrate and phosphate concentrations in septic tank leachate were assumed to be 70 and 7 g m^{-3} respectively, based on previous model applications which included septic tanks.

Total nitrogen and phosphorus loads to Lake Tikitapu estimated using the above methodology were 2322.4 and 92.8 kg yr^{-1} respectively – broadly comparable to the estimates of 2502 and 125 kg yr^{-1} presented in McIntosh (2010).

2.9 Simulation periods and model initialisation

For all simulations the model was initialised using a start date of 01 July (day 182), after the water column had undergone winter mixing. Water quality data collected by BoPRC nearest to the start of simulation date were used in the initialisation (*.int) file, and values were set as constant throughout the (mixed) water column. Separate simulation periods were allocated for model calibration and validation, of 2005 to 2010 and 2001 to 2005 respectively. The calibration period was also used for scenario simulations.

2.10 Analysis of model performance

Model performance was assessed by comparing model output with field observations from BoPRC's 'environmental data survey' monitoring programme. For each measured parameter, the difference between the value from monthly field measurements and model output from the corresponding day was calculated. These differences were used to calculate model error statistics, including Pearson correlation coefficient (R), mean absolute error (MAE), and root mean squared error (RMSE). The normalised error metrics normalised mean absolute error (NMAE) and normalised root mean squared error (NRMSE) were calculated by dividing the MAE and RMSE by the average of all field measurements for the relevant parameter.

2.11 Simulated action plan scenario – reticulation of sewage

An important management action in the Lake Tikitapu action plan (BoPRC. 2011) was the reticulation of sewage in the catchment, primarily from the public toilets and campground adjacent to the lake. In order to simulate the effects of this reticulation, a scenario was established whereby the septic tank inflow to the lake was removed (inflow volume set to zero). Model output was compared with baseline simulations, and a trophic level index (TLI3) was calculated to compare the baseline and reticulated scenarios.

2.12 Simulated action plan scenario – increased silica diffusion from lake sediments

The rate of diffusion of silica from lake sediments to the water column has been previously estimated as approximately 0.17 mg cm^{-2} y^{-1} (L. Pearson, *pers. comm*.). Multiple sediment cores collected from Tikitapu on at least four occasions prior to 2011 consistently showed surface layers of elevated organic matter of c. 7 cm depth. However, in an April 2012 survey (UoW) most cores showed very little organic sediment with erosion to near the top of the Tarawera Tephra, while a few cores showed thick organic sediment mixed with reworked Tarawera Tephra. It was suggested that this redistribution of sediments in the lake, exposing previously buried sediments higher in silica, could result in a greater than 5-fold increase in the internal load of silica to the water column (C. Hendy, *pers. comm.*). In order to approximate the effects of this change on algal production in Lake Tikitapu, a scenario with increased silica diffusion from lake sediments was simulated. For the baseline (calibration) scenario, internal silica release was set in order to approximate the previously estimated internal load of 0.17 mg cm^{-2} y^{-1}. For the scenario of increased diffusion, the maximum release rate for silica was multiplied by 5.5 to represent the potential increase to internal silica load described above.

3 Results

3.1 Model calibration

The model parameters adjusted during the calibration of DYRESM and CAEDYM are presented in Tables 3 and 4, respectively. Parameter values were assigned mostly within the range found in the literature (e.g., Schladow and Hamilton 1997; Trolle et al. 2008, Özkundakci et al., 2011). Visual comparisons of simulated temperature, dissolved oxygen, nitrate, ammonium, TN, phosphate and TP concentrations with field measurements are presented in Figure 10 and comparisons of chlorophyll *a* concentrations are shown in Figure 11.

Table 3. Assigned values for parameters used in DYRESM.

Parameter	Unit	Calibrated value	Reference
Critical wind speed	$m\ s^{-1}$	5.0	Best fit to data
Emissivity of water surface	-	0.96	Imberger & Patterson (1981)
Mean albedo of water	-	0.08	Patten et al. (1975)
Potential energy mixing efficiency	-	0.2	Spigel et al. (1986)
Shear production efficiency	-	0.3	Best fit to data
Wind stirring efficiency	-	0.3	Best fit to data
Vertical mixing coefficient	-	200	Best fit to data
Effective surface area coefficient	m^2	1.8×10^6	Best fit to data

Table 4. Assigned values for parameters used in CAEDYM for Lake Tikitapu; DOPL and DONL are dissolved organic phosphorus and nitrogen, respectively.

Parameter	Unit	Calibrated value	Reference source
Sediment parameters			
Sediment oxygen demand	$g\ m^{-2}\ d^{-1}$	0.5	Schladow & Hamilton (1997)
Half-saturation coefficient for sediment oxygen demand	$mg\ L^{-1}$	0.5	Schladow & Hamilton (1997)
Maximum potential PO_4 release rate	$g\ m^{-2}\ d^{-1}$	0.0003	Best fit to data
Oxygen and nitrate half-saturation for release of phosphate from bottom sediments	$g\ m^{-3}$	0.5	Best fit to data
Maximum potential NH_4 release rate	$g\ m^{-2}\ d^{-1}$	0.002	Best fit to data
Oxygen half-saturation constant for release of ammonium from bottom sediments	$g\ m^{-3}$	0.2	Best fit to data
Maximum potential NO_3 release rate	$g\ m^{-2}\ d^{-1}$	-0.01	Best fit to data
Oxygen half-saturation constant for release of nitrate from bottom sediments	$g\ m^{-3}$	0.9	Best fit to data
Maximum potential Si release rate	$g\ m^{-2}\ d^{-1}$	0.018	Best fit to data
Oxygen half-saturation constant for release of silica from bottom sediments	$g\ m^{-3}$	8.0	Best fit to data
Temperature multiplier for nutrient release	-	1.05	Robson & Hamilton (2004)
Nutrient parameters			
Decomposition rate of POPL to DOPL	d^{-1}	0.001	Best fit to data
Mineralisation rate of DOPL to PO_4	d^{-1}	0.008	Best fit to data
Decomposition rate of PONL to DONL	d^{-1}	0.001	Best fit to data
Mineralisation rate of DONL to NH_4	d^{-1}	0.002	Best fit to data
Denitrification rate coefficient	d^{-1}	0.03	Best fit to data
Oxygen half-saturation constant for denitrification	$mg\ L^{-1}$	1.5	Best fit to data
Temperature multiplier for denitrification	-	1.07	Best fit to data
Nitrification rate coefficient	d^{-1}	0.07	Schladow & Hamilton (1997)
Nitrification half-saturation constant for oxygen	$mg\ L^{-1}$	5.0	Schladow & Hamilton (1997)
Temperature multiplier for nitrification	-	1.08	Best fit to data
Phytoplankton parameters		**Diatoms, chlorophytes**	
Maximum potential growth rate at 20°C	d^{-1}	1.11, 1.15	Best fit to data
Irradiance parameter non-photoinhibited growth	$\mu mol\ m^{-2}\ s^{-1}$	15, 100	Schladow & Hamilton (1997)
Half saturation constant for phosphorus uptake	$mg\ L^{-1}$	0.003, 0.003	Best fit to data
Half saturation constant for nitrogen uptake	$mg\ L^{-1}$	0.01, 0.01	Best fit to data
Minimum internal nitrogen concentration	mg N (mg chl *a*)$^{-1}$	1.0, 3.0	Schladow & Hamilton (1997)
Maximum internal nitrogen concentration	mg N (mg chl *a*)$^{-1}$	9.0, 10.0	Schladow & Hamilton (1997)
Maximum rate of nitrogen uptake	mg N (mg chl *a*)$^{-1}$ d^{-1}	0.8, 1.5	Schladow & Hamilton (1997)
Minimum internal phosphorus concentration	mg P (mg chl *a*)$^{-1}$	0.1, 0.1	Schladow & Hamilton (1997)
Maximum internal phosphorus concentration	mg P (mg chl *a*)$^{-1}$	2.0, 2.0	Schladow & Hamilton (1997)
Maximum rate of phosphorus uptake	mg P (mg chl *a*)$^{-1}$ d^{-1}	0.25, 0.15	Schladow & Hamilton (1997)
Constant internal silica concentration	mg Si (mg chl *a*)$^{-1}$	180.0, 0.0	
Half saturation constant for silica uptake	$mg\ L^{-1}$	0.2, 0.0	Martin-Jezequel et al (2000)
Temperature multiplier for growth limitation	-	1.04, 1.06	Schladow & Hamilton (1997)
Standard temperature for growth	°C	14.0, 18.0	Coles & Jones (2000)
Optimum temperature for growth	°C	22.0, 25.0	Coles & Jones (2000)
Maximum temperature for growth	°C	31.0, 38.0	Coles & Jones (2000)
Respiration rate coefficient	d^{-1}	0.08, 0.1	Schladow & Hamilton (1997)
Temperature multiplier for respiration	-	1.06, 1.06	Schladow & Hamilton (1997)
Fraction of respiration relative to total metabolic loss rate	-	0.7, 0.7	
Fraction of metabolic loss rate that goes to DOM	-	0.7, 0.7	
Constant settling velocity	$m\ s^{-1}$	-1.0×10^{-5}, -2.3×10^{-6}	Modified from: Burger et al. (2007a)

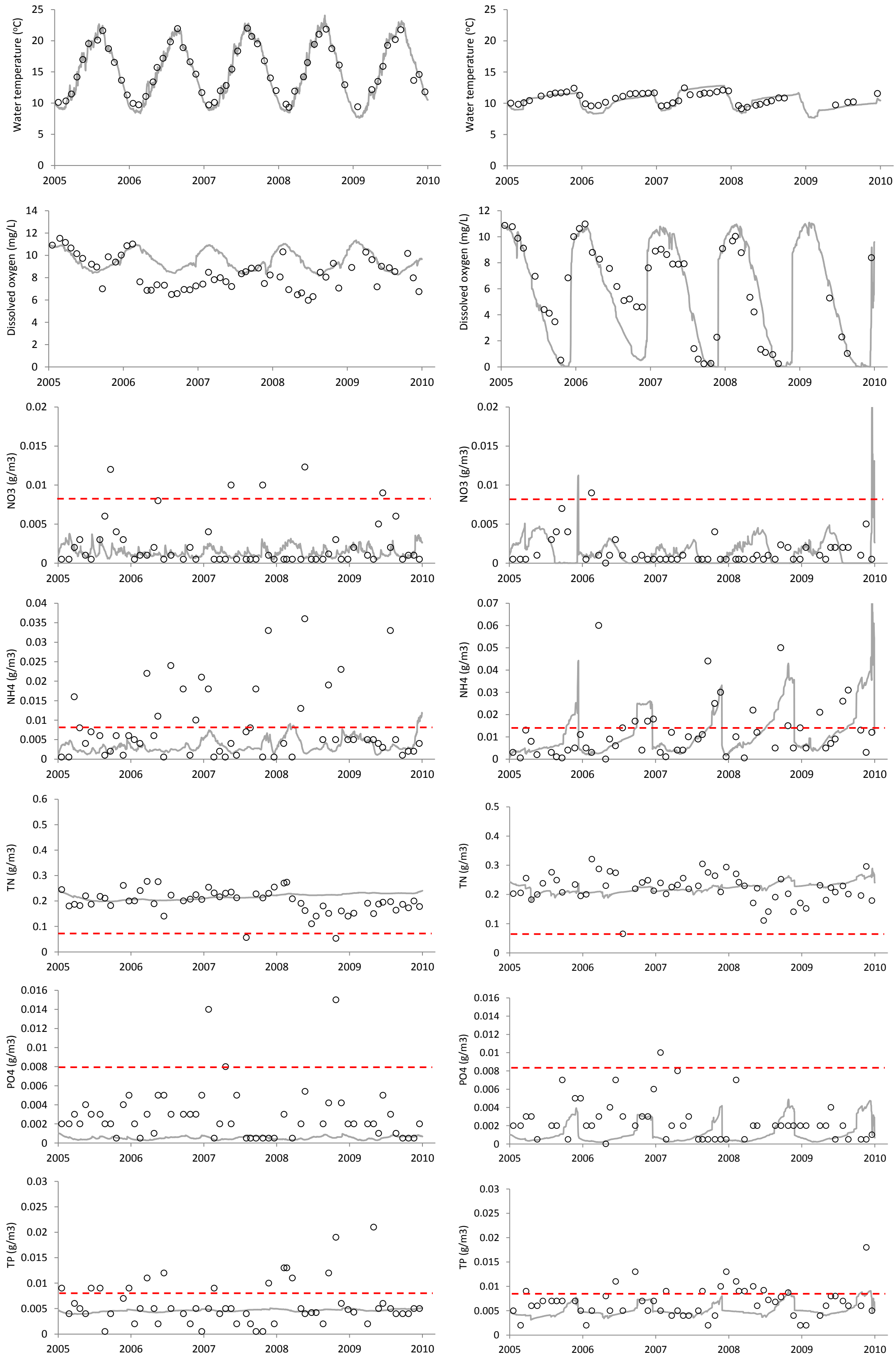

Figure 10. Comparison of model simulations (grey line) against field observations (circles) at the surface (0 m; left hand plots) and near-bottom (23 m; right hand plots) of Lake Tikitapu during the calibration period for temperature, dissolved oxygen, nitrate, ammonium, total nitrogen (g N m^{-3}), phosphate and total phosphorus (g P m^{-3}). Dashed red lines represent analytical detection limits (BoPRC, pers. comm.).

Table 5. Statistical comparison between model simulations and field data (monthly measurements) of surface (0 m), and bottom (23 m) waters in Lake Tikitapu using Pearson correlation coefficient (R), mean absolute error (MAE), mean observation-normalised mean absolute error (NMAE), root mean squared error (RMSE) and mean observation-normalised root mean squared error (NRMSE), for the calibration period.

SURFACE

	R	MAE	NMAE	RMSE	NRMSE
Temperature	0.991	0.586	0.038	0.759	0.050
Dissolved oxygen	0.298	1.461	0.174	1.832	0.218
Nitrate	-0.175	0.002	0.866	0.003	1.456
Ammonium	-0.052	0.007	0.818	0.010	1.267
Total nitrogen	-0.264	0.041	0.206	0.054	0.274
Phosphate	-0.017	0.002	0.834	0.004	1.271
Total phosphorus	-0.046	0.003	0.484	0.004	0.748
Total chlorophyll	0.364	0.750	0.404	0.954	0.515

DEEP

	R	MAE	NMAE	RMSE	NRMSE
Temperature	0.832	0.641	0.059	0.725	0.067
Dissolved oxygen	0.763	1.790	0.278	2.733	0.425
Nitrate	-0.140	0.002	1.353	0.003	2.332
Ammonium	0.223	0.012	0.885	0.019	1.439
Total nitrogen	-0.127	0.059	0.246	0.126	0.523
Phosphate	-0.188	0.002	0.852	0.003	1.170
Total phosphorus	0.169	0.003	0.437	0.005	0.629

Metrics for model performance (Table 5) indicate acceptable model comparison with field data relative to literature precedents. The key model components temperature, dissolved oxygen, and chlorophyll *a* were generally well represented by the model, as shown by strongly positive values for R and low error values. Unusually, field data for summer 2006-2007 show strong seasonal thermal stratification but relatively high dissolved oxygen concentrations in bottom waters relative to other years. This anomaly was not particularly well simulated by the model.

Because of Lake Tikitapu's relatively low nutrient status, and the analytical methods employed, lake water column nutrient measurements were often below analytical detection limits for many nutrient species (e.g. 0.008 g m^{-3} for dissolved reactive phosphorus, Figure 10). This not only made calibration more difficult, but also meant that error metrics were not a reliable indicator of model performance for some simulated variables. This was particularly so for dissolved nutrient species. Further, low *in situ* concentrations may have increased the relative influence of any sample contamination. Although normalised error metrics were relatively low for total nitrogen and phosphorus concentrations, intra-annual variability was not well simulated by the model. This is likely because lake inflows were prescribed constant nutrient concentrations due to the infrequency of field observations with which to characterise inflow water quality.

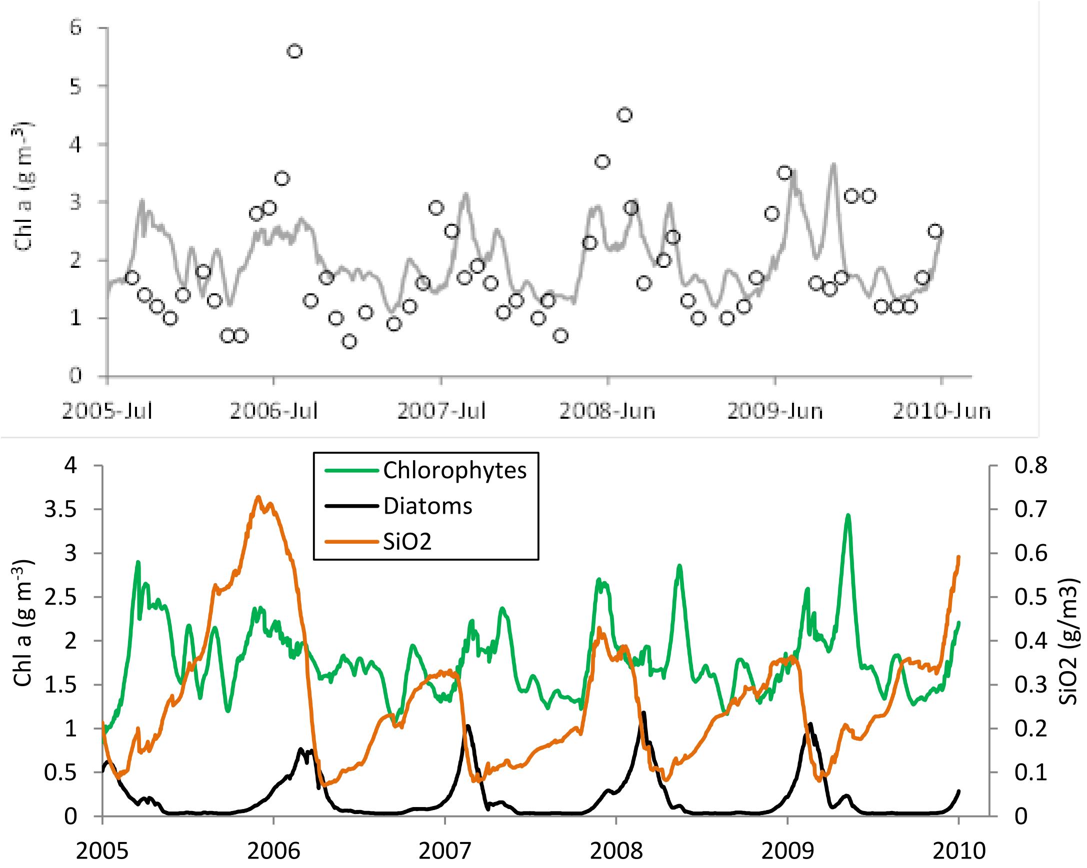

Figure 11. A) Comparison of chlorophyll a model simulations (lines) against field observations (circles) at the surface (0 m) of Lake Tikitapu during the calibration period. B) Model simulations of chlorophytes, diatoms and silicon dioxide over the calibration period.

Chlorophyll (phytoplankton) dynamics were well simulated by the calibrated model (Figure 11a, R = 0.364), and the general dominance of chlorophytes (Figure 2) was well represented (Figure 11b). Modelled growth of diatoms was most strongly limited by availability of silica in the water column (Figure 11b), consistent with previous descriptions of algal production in the lake (Ryan 2006). The model showed some evidence of a simulated 'deep chlorophyll maximum' during periods of seasonal stratification (Figure 12). This phenomenon is common in lakes of relatively high water quality, and is frequently observed at Lake Tikitapu in BoPRC monitoring data (e.g. Figure 13). Although the simulated DCM was less pronounced than suggested by some BoPRC fluorescence profiles, this may be due to non-photochemical quenching (NPQ) of fluorescence measurements near the water column surface in measured profiles taken during relatively high ambient solar radiation.

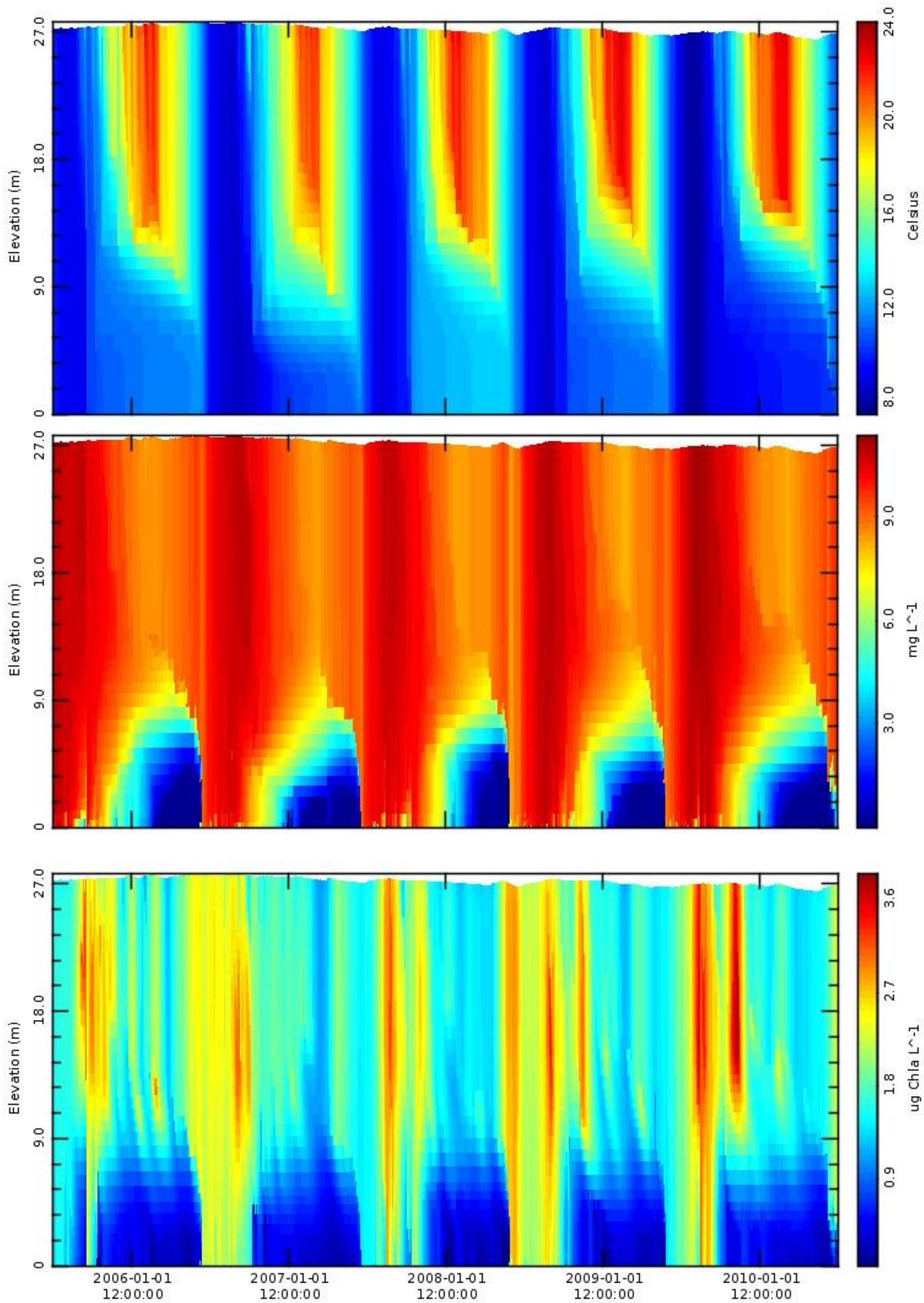

Figure 12. Model simulations of A) temperature, B) dissolved oxygen, and C) total chlorophyll a at Lake Tikitapu during the calibration period.

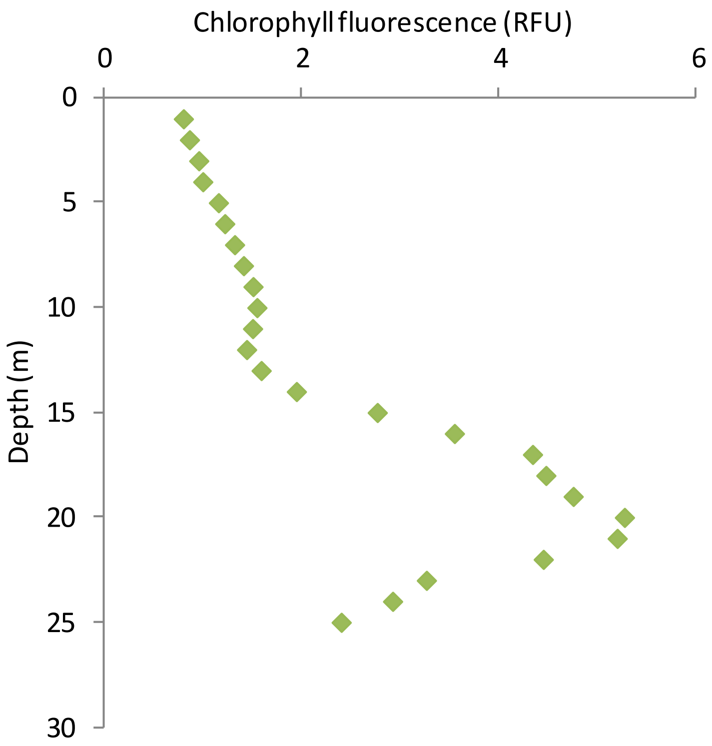

Figure 13. Chlorophyll fluorescence (relative fluorescence units) vs. depth on 22/12/2008 in Lake Tikitapu (BoPRC environmental data survey).

3.2 Model validation

Calibrated DYRESM-CAEDYM parameters were used to simulate the period Jul 2001 – Jun 2005. Model performance was evaluated similarly to the calibration period, in order to assess the robustness of the model calibration when applied to independent time periods. Visual comparisons for the state variables are presented in Figure 14, and model error statistics in Table 6. Model performance over the validation period was generally comparable, and sometimes improved relative to the calibration period, indicating satisfactory model performance.

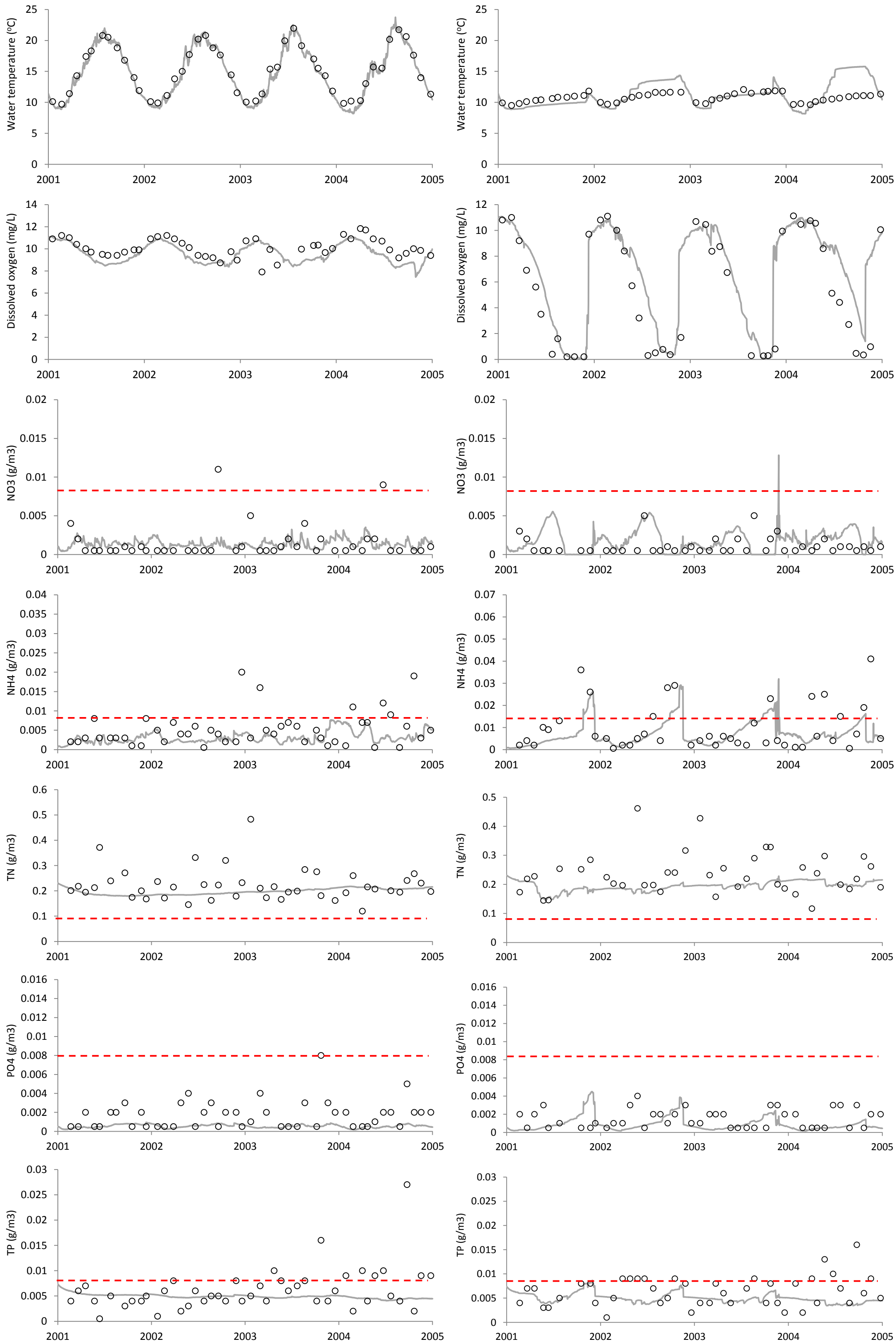

Figure 14. Comparison of model simulations (grey line) against field observations (circles) at the surface (0 m; left hand plots) and near-bottom (23 m; right hand plots) of Lake Tikitapu during the validation period for temperature, dissolved oxygen, nitrate, ammonium, total nitrogen (g N m^{-3}), phosphate and total phosphorus (g P m^{-3}). Dashed red lines represent analytical detection limits (BoPRC, pers. comm.).

Table 6. Statistical comparison between model simulations and field data (monthly measurements) of surface (0 m), and bottom (23 m) waters in Lake Tikitapu using Pearson correlation coefficient (R), mean absolute error (MAE), mean observation-normalised mean absolute error (NMAE), root mean squared error (RMSE) and mean observation-normalised root mean squared error (NRMSE), for the validation period.

SURFACE

	R	MAE	NMAE	RMSE	NRMSE
Temperature	0.995	0.501	0.034	0.608	0.041
Dissolved oxygen	0.632	0.742	0.073	0.880	0.087
Nitrate	-0.003	0.004	0.939	0.015	3.593
Ammonium	-0.028	0.003	0.654	0.005	0.991
Total nitrogen	-0.108	0.045	0.201	0.070	0.316
Phosphate	0.160	0.001	0.721	0.002	1.094
Total phosphorus	-0.285	0.003	0.443	0.005	0.733
Total chlorophyll	0.296	0.988	0.417	1.244	0.525

DEEP

	R	MAE	NMAE	RMSE	NRMSE
Temperature	0.635	1.313	0.123	1.869	0.174
Dissolved oxygen	0.868	1.599	0.295	2.553	0.471
Nitrate	0.010	0.001	1.350	0.002	1.726
Ammonium	0.258	0.007	0.666	0.014	1.283
Total nitrogen	0.075	0.056	0.238	0.081	0.344
Phosphate	-0.125	0.001	0.757	0.001	0.984
Total phosphorus	-0.122	0.004	0.495	0.008	1.119

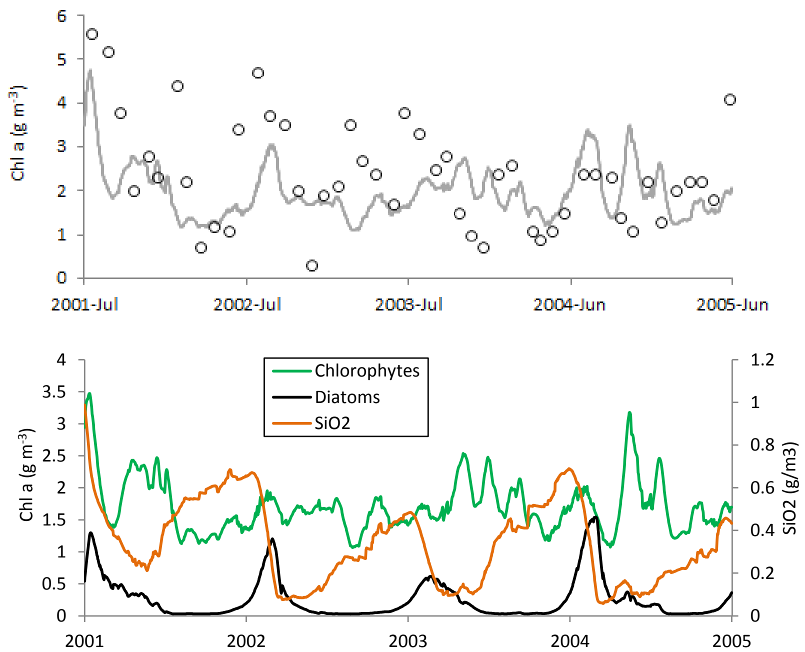

Figure 15. A) Comparison of chlorophyll a model simulations (line) against field observations (circles) at the surface (0 m) of Lake Tikitapu during the validation period. B) Model simulations of chlorophytes, diatoms and silicon dioxide over the validation period.

3.3 Modelled 'Action Plan' scenario – reticulation of sewage.

Removal of the septic tank nutrient load to Lake Tikitapu resulted in a substantial reduction of both phosphorus and total nitrogen in the water column. Accordingly, concentrations of chlorophyll *a* (as a proxy for phytoplankton biomass) also decreased, however, diatoms were relatively unaffected by the lower nutrient loads, presumably because silica rather than nitrogen or phosphorus was the primary limiting resource. Trophic level indices were calculated for the baseline and scenario simulations. Because CAEDYM does not simulate water clarity, a three parameter index (TLI3) was used to indicate the overall change in water quality. A reduction of 0.6 TLI units was simulated following removal of the septic tank inflow (Table 7), with the greatest reduction in phosphorus concentrations observable at least a year after septic tanks are removed (Figure 16b). Conversely, it takes at least two to three years before the effect of septic tank removal on simulated total nitrogen becomes pronounced. Reduction in diatoms was not significant upon removal of septic tanks. Instead, alternating increases and decreases of diatom levels were observed in the simulation upon septic tank removal (Figure 16d).

Table 7. Trophic level indices for total nitrogen (TLn), total phosphorus (TLp), total chlorophyll a (TLc), and three-parameter trophic level index (TLI3), for the baseline calibration and the septic tank removal scenario over the period 2005 – 2010.

	TLn	TLp	TLc	**TLI3**
Baseline	3.4	2.2	3.0	**2.8**
No septic	3.2	1.2	2.2	**2.2**

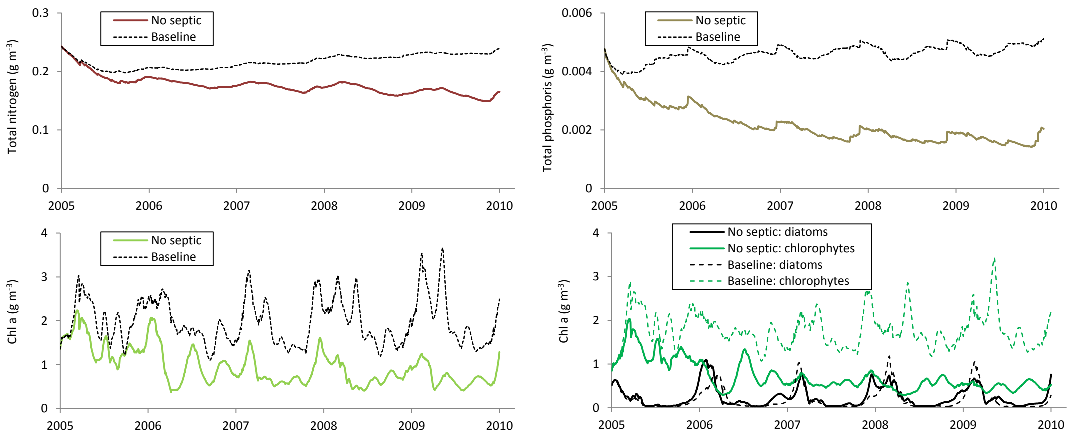

Figure 16. Comparisons of baseline (calibration) simulations and scenario (removal of septic tanks within the catchment) simulations, for A) total nitrogen, B) total phosphorus, C) total chlorophyll a, and D) diatoms and chlorophytes, over the period July 2005 to June 2010.

3.4 Modelled scenario – increased silica diffusion from lake sediments.

A dramatic (5.5-fold) increase in the diffusion of silica from lake sediments (internal load), resulted in a slight increase in diatom production, and a corresponding decrease in chlorophyte production. Overall chlorophyll concentrations (phytoplankton biomass) and total nutrient concentrations were relatively unaffected (Figure 17). The internal load of silica in the baseline simulations was less than 2.5 t y^{-1}, therefore the scenario load would be less than 13.5 t y^{-1}. By comparison, the estimated (modelled) external load of silica was c. 30 t y^{-1}. This explains why the observed increase in diatom growth was relatively small between the scenario and baseline simulations. It should be noted that the estimation of external silica load was based on limited field observations of groundwater concentrations.

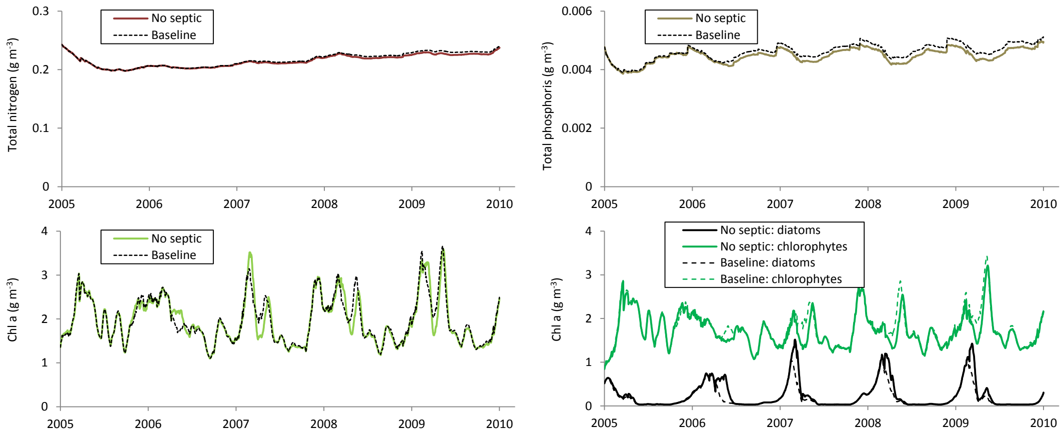

Figure 17. Comparisons of baseline (calibration) simulations and scenario (5.5-fold increase in silica diffusion from lake sediments) simulations, for A) total nitrogen, B) total phosphorus, C) total chlorophyll a, and D) diatoms and chlorophytes, over the period July 2005 to June 2010.

4 Discussion

4.1 Model performance

The objective of this project was to establish a DYRESM-CAEDYM model, providing a basis for future use as a decision support tool for management of Lake Tikitapu and its catchment.

Catchment and lake water balances, derived from relatively limited field observations, provided a basis for inflows volumes which resulted in relatively stable water levels that closely matched observed water level changes. Performance of the calibrated hydrodynamic-ecological model was generally highly satisfactory. Error values for several parameters were comparable or better than previously published applications of DYRESM-CAEDYM. At instances where poor model error metrics were observed, field measurements were often at or below analytical detection limits, which confounded accurate simulation and assessment of model performance.

Key processes in Lake Tikitapu were well represented by the calibrated model. The simulated balance of algal taxa approximated observations by BoPRC monitoring. Simulated growth of diatoms was limited by availability of silica, as is generally thought to be the case in Tikitapu (McColl 1972, Ryan 2006) due to relatively low concentrations of silica (c. 0.22 mg L^{-1}, BoPRC, *unpubl. data*). Furthermore, the model simulated to some extent the settling of negatively buoyant algae and the periodic formation of deep chlorophyll maxima in the lake, as observed by BoPRC's monitoring program.

4.2 Model constraints

Lake Tikitapu is an ideal candidate for the application of a one-dimensional hydrodynamic model such as DYRESM. It is small and bowl-shaped, and vertical variation is greater than horizontal variation.

Due to the limited availability of important forcing data such as local meteorology, inflow and outflow discharge measurements, as well as temporally resolved measurements of inflow nutrient concentrations, several conceptual simplifications were made in the model. The most important of these assumptions were static inflow nutrient concentrations (based on a single analysis of groundwater nutrient concentrations at several sites), and inflow and outflow volumes derived via a catchment water balance (including relatively crudely modelled catchment evapotranspiration rates).

The current model application does not include additional food web components such as macrophytes, microphytobenthos, zooplankton or fish. As has been suggested for other model applications in the region (e.g. Özkundakci et al. 2011), this could have consequences for the model performance and scenario outcomes. In this model application, the contribution of higher biology to water column nutrient pools and algae mortality via zooplankton grazing was approximated by slightly elevated coefficients for algae respiration and mortality.

Long-term changes in sediment nutrient pools are not simulated by CAEDYM. In a recent application of CAEDYM to Lake Rotorua, this was addressed by introducing a semi-dynamic response (Hamilton et al. 2012). This is likely not applicable to the Lake Tikitapu model, because of lack of long-term data (i.e. decades) for external nutrient loading – this was not the case in Rotorua where catchment nutrient inputs were based on ROTAN model outputs.

4.3 Action plan scenario: sewage reticulation

Removal of nutrient loads to the lake from septic tanks resulted in improved water quality and a 0.6 reduction in the three-parameter (TN, T and chlorophyll *a*) TLI. This suggests that reticulation of sewage in the catchment may well achieve or exceed the desired water quality to maintain the intrinsic, cultural and economic benefits of Lake Tikitapu to the Bay of Plenty region. The scenario simulation (i.e., removing septic tanks) suggested that it may take at least two years to fully realise the benefits of reticulation.

4.4 Scenario: increased silica diffusion

Phytoplankton biodiversity in Lake Tikitapu has been observed to be relatively low, largely dominated by chlorophytes. Low water column silica is presumed to be limiting to growth of diatoms in Lake Tikitapu (McColl 1972, BoPRC *pers. comm.*), thus increases in internal silica load could affect phytoplankton biodiversity in the lake. Recent sediment surveys have indicated a redistribution of sediments in the lake, perhaps due to speculated seismic or geothermal activity, that has exposed deeper sediments in much of the lake and could result in greatly increased diffusion of silica from sediments (C. Hendy, *pers. comm.*). Simulations of this increased internal load showed a relatively small increase in diatom production in response to a 5.5-fold increase to internal load. The increased internal silica load was still less than half of the modelled external load. It is noted that the estimation of external and internal silica loads to the lake was based on limited data and as such was likely subject to high uncertainty. More comprehensive field observations would be required in order to better understand the likely magnitude of, and lake response to, any change in internal silica diffusion.

4.5 Recommendations

BoPRC's program of monthly lake water quality monitoring is highly valuable for understanding processes and long-term change in the Rotorua lakes, as well as for calibration and validation of lake models. Supplementary field observations in Lake Tikitapu and its catchment could improve understanding of the lake-catchment ecosystem, and might substantially improve the utility and performance of the lake model presented here. Useful data could include:

- Surface inflows: better characterisation of ephemeral surface discharge and water chemistry could improve the water balance and nutrient dynamics within the model.
- Groundwater monitoring: based on speculation that the majority of inflow volume to Tikitapu is via groundwater, more thorough analysis of groundwater nutrient concentrations within the catchment could refine the catchment nutrient budget. Further, by introducing seasonal variability of inflow water quality to the model, improvements may be gained in the characterisation of total nitrogen and phosphorus dynamics.
- Characterisation of nutrient 'pulses' from harvesting of plantation forestry
- Specific aspects of interannual variation, for example, DCM formation, dissolved oxygen depletion rates and duration of anoxia. A profiling monitoring buoy, as installed in Lake Rotoehu, would comprehensively measure these dynamics and enable detailed consideration of drivers (e.g. climate).
- Regular enumeration and biomass estimation for phytoplankton and zooplankton (e.g. quarterly)

Several biological components were excluded from the present model application, for reasons of practicality. Benthic primary production by micro-algae and cyanobacteria (periphyton) is thought to be of importance to Lake Tikitapu (Wood et al. 2011, M. Gibbs *pers. comm.*), as well as a potential source of cyanotoxin to the lake food web (Wood et al. 2012). Field observations of benthic respiration and sediment chlorophyll, measured by the National Institute of Water and Atmospheric Research (NIWA), could be leveraged upon for the inclusion of benthic production within the model. However, this would require model development using either a conceptual proxy within the existing CAEDYM model (e.g. seagrass without salinity limitation) or by incorporating a new module within the current model. Similarly, the inclusion of submerged macrophytes in the lake model would require continued monitoring of weed beds (see Burton & Clayton 2014), as well as a full vegetation study to estimate biomass.

Finally, recent improvements in analytical methods, post-2009 (BoPRC, *pers. comm.*), may enable a more accurate calibration and assessment of model performance at low nutrient concentrations, if at some point in the future the model were extended and run for the period, for example, 2009 to 2015.

5 Conclusions

A functional DYRESM-CAEDYM model of Lake Tikitapu has been established, with representation of water and nutrient sources to and from the lake. Although the model demonstrated acceptable performance as indicated by model error statistics, opportunities exist for improving the accuracy and usefulness of the current model, including refinement of input data, incorporation of additional biological components such as microphytobenthos, and extension of the date range covered by the model. More in-depth evaluation of model performance can also be undertaken for dissolved nutrients for which the low levels in the lake can be better assessed in view of improvements in analytical detection limits.

An initial simulation of sewage reticulation in the Tikitapu catchments indicates that this action may be sufficient to meet the Trophic Level Index target stipulated in the Lake Tikitapu Action Plan (BoPRC, 2011), and may take upwards of two years for the benefits to the lake to be fully realised. The established model can be used for testing various scenarios of lake management actions, and should be considered as a useful ‘decision support tool’.

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