Modelling of restoration scenarios for Lake Ngaroto

CBER Report 81

Report prepared for Waipa District Council

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Photo: Warrick Powrie

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Executive summary

Waipa District Council is investigating restoration options for Lake Ngaroto, a shallow lake that has become hypertrophic through high external (catchment) nutrient loading from its catchment, which is associated with land use that is predominantly dairy farming. Shallow lakes like Lake Ngaroto, which have high external loading, typically have high internal nutrient loading, which may also need to be addressed to gain immediate improvements in water quality. By contrast, reduction of external nutrients is more likely to be associated with gradual and long-lasting effects on water quality.

This report is a culmination of data collection and analysis, and model development and simulation of restoration scenarios for Lake Ngaroto. Data were gathered on flow, nutrient concentrations, temperature, dissolved oxygen, suspended sediments, meteorological variables and the lake morphology for the lake and its catchment. These data were used to produce a water balance and input files for DYRESM-CAEDYM, a one dimensional, coupled hydrodynamic-water quality model. Once calibrated, using the measured lake data (ammonium (NH_4-N), nitrate (NO_3-N), phosphate (PO_4-P), total phosphorus (TP), total nitrogen (TN), chlorophyll *a* (Chl *a*), suspended solids (SS), temperature, dissolved oxygen (DO)) as a means of comparison for modelled data, a number of scenarios were carried out to simulate outcomes of lake restoration measures.

A period of one year (Dec 2006 to Dec 2007) was chosen in which to carry out the simulations. The available data set for calibration was from Dec 2006 to May 2007, and consisted of 15 flow measurements (Dec 2006 to Sept 2007) and 12 in-lake measurements of nutrients, DO, Chl *a* and SS, with a and calibrated against the in-lake measurements. Additional data required for the model input was derived through a combination of averaging or using theoretical or statistical relationships. With such a large proportion of the model reliant on these estimates there is a greater component of error in the model output.

The lake water quality restoration scenarios simulated included diverting the major inflow from Lake Ngarotoiti (inflow D13) into the outflow (D14), increasing and decreasing the lake water level by 0.4 m, reducing the external nutrient load by 33 and 50%, reducing the wind speed by 50% and removal of the upper 20 cm of sediment from the lake bottom. Most of these scenarios produced predictable results, with reduction of internal nutrient load having a much stronger and beneficial impact on water quality than reducing external nutrient load. Sediment removal produced the most beneficial change (reduction of nutrients and Chl *a*) whereas reduction of external nutrient load through change of land use had only a modest effect over two years. Lowering the water level and adding wind barriers reduced suspended sediments but increased nutrients and Chl *a*. Diversion of the major inflow and raising the lake level resulted in only small changes. The positive effects from sediment removal are an indication of the strong influence of internal nutrient loads on lake water quality in Lake Ngaroto whereas the influence of external loading on water quality is a long term effect that is expressed to a limited extent over a duration of two years. It is important to emphasise, however, that it is the external load that maintains an ongoing source of nutrients to support the internal load, so both external and internal nutrient loading should be addressed in an integrated management plan for the lake.

In a previous report by Faithfull *et al*. (2005), reduction of nutrient release from sediments through removal by, for example, suction dredging, was considered an expensive

management option. It presented potential difficulties with disposal of the sediments, and sediments at a depth of 20 cm had high levels of phosphate. If this option is to be considered, however, then small-scale trials could be considered and more detailed assessment given to options for managing the sediments removed from the lake. Similarly, the use of flocculents for inactivating phosphorus would require both lab and field based trials, though compounds such as a modified zeolite developed by Scion (Rotorua) show considerable promise for this purpose. A programme of removal of pest fish should be undertaken with any restoration procedure, as part of an integrated lake management plan. Comprehensive and consistent monitoring of inflows, outflows and the lake is also recommended so that baseline data against which any changes from future actions can be measured is set, and refinements to model predictions can be produced.

1 Introduction

Lake Ngaroto is located 19 km south of Hamilton City and 8 km northwest of Te Awamutu, near State Highway 3. It is popular for recreational uses including fishing, rowing, hunting and sailing, and a walkway surrounding the lake is well-used (MfE, 2001). It is the largest peat lake in the Waipa District and ecologically it has many similarities to the other peat lakes of the Waikato basin. The lake (and the other lakes in the Waikato Basin) was formed 19,000 years before present as a result of the Waikato River changing its course and carrying a flood of alluvium with it. The alluvium was deposited downstream in the Waikato Basin and blocked off small streams, producing small lakes which eventually turned into peat lakes and bogs (McGraw, 2002). Archaeological evidence from five pa sites around Lake Ngaroto indicates that Maori people lived here and that they cultivated their own food as well as using the nearby forest and lake as a food source (Amess *et al*. 1978). The area was also important in times of war and Lake Ngaroto was the scene of one of the largest battles between Maoris and Europeans (Ames *et al*. 1978) as well as the battle the Battle of Hingakaka. The latter battle took place around 1803 on the shores of Lake Ngaroto when an army of around 10,000 Māori warriors of several tribes attempted to settle a long-running grievance by destroying a settlement of 3,000 men, women and children, mostly from the Ngati Maniapoto tribe, who lived on the shores and on the island of Lake Ngaroto. The shoreline dwellers used great stealth as well as familiarity with their local wetland and lake environment to kill many of the invaders, some of whom were forced to swim for safety in the lake, only to drown or be dispatched of as they attempted to return to shore. Around one century later, as the wetlands around the lake were drained and the lake water level decreased to support agricultural development, not only were the bones of many who drowned in the lake uncovered but also a carving was discovered in which a stone was embedded. This stone is reputed to hold one of the traditional gods of the Māori people, Uenuku, and was brought across the Pacific Ocean to New Zealand in a canoe by some of the first Māori settlers of the Tainui tribe. Uenuku had apparently been placed in Lake Ngaroto for safe-keeping during the battle of Hingakaka and is today housed in the Te Awamutu museum.

Modifications of the catchment area to support agricultural development have resulted in the lake water level falling by approximately 2 m from its historic levels (Ministry for the Environment (MfE), 2001; Faithfull *et al*. 2005). Today the land use of the catchment is 1416 ha dairy pasture, 270 ha drystock pasture and 60 ha non-agricultural use (Environment Waikato, 2006). Lake Ngaroto has an external nutrient load of 54.74 t N yr^{-1} and 0.79 t P yr^{-1} based on values for respective nutrient losses of nitrogen (N) and phosphorus (P) of 36 kg N ha^{-1}yr^{-1} and 0.5 kg P ha^{-1}yr^{-1} for dairying, 13 kg N ha^{-1}yr^{-1} and 0.3 kg P ha^{-1}yr^{-1} for drystock, and 3 kg N ha^{-1}yr^{-1}) and 0.1 kg P ha^{-1}yr^{-1} for non-agricultural land use in the Waikato region (Ledgard and Power, 2006).

Changes in land use in the catchment have greatly impacted on the Lake Ngaroto water quality (MfE, 2001) resulting in a 'Trophic Level Index' (TLI) classification of 'hyper-trophic` (Hamill & Lew, 2006). The TLI calculation is based on TN, TP and chlorophyll *a* concentrations, and Secchi depth, the water clarity variable. Due to the shallow nature of Lake Ngaroto (mean depth <2 m) and absence of macrophytes, concentrations of suspended solids are high, which contributes to poor water clarity. In the 1980s some ecological restoration attempts were made, including placing a weir on the main outflow to regulate the water levels, building sediment traps on the main inflows, riparian planting and establishing a fenced reserve margin (MfE, 2001). Lake Ngaroto has recurrent algal blooms which are dominated by *Microcystis* spp. and *Aulacoseira* spp. (unpub. data), supported by high concentrations of bio-available nutrients. General characteristics of Lake Ngaroto are given in Table 1.

The initial purpose of this study was to set up a computer model (DYRESM-CAEDYM) for Lake Ngaroto. In-lake and inflow/outflow data from a previous investigation carried out from Dec 2006 to the end of Jan 2007 (Beaton *et al*., 2007) were used to augment the data (Mar to May 2007) to capture seasonal variation of the lake water quality more accurately. Model simulations were extended to a full year using additional water quality and flow data (Aug 2007 to Sept 2007) from the inflows (D1, 2 and 13) and the outflow (D14) provided by Tony Roxburgh (Waipa District Council) (Appendix 2), meteorological data from NIWA and water level data from Environment Waikato. An intensive calibration procedure was undertaken against in-lake measurements and, when a satisfactory calibration has been achieved, simulations were undertaken of various restoration scenarios to alter internal and external nutrient loading and SS concentrations. This report includes the analytical methods and results for 7 Mar to 29 May 2007 for the inflows and lake in the results and (Appendix 1) and for Aug to Sept 2007 (Appendix 2).

Table 1: Characteristics of Lake Ngaroto

Area	108 ha (Barnes, 2002)
Maximum depth	4 m (Barnes, 2002)
Mean depth	< 2m (Barnes, 2002)
Trophic State	Hypertrophic (Barnes, 2002)
Recreation	Sailing, rowing, game bird hunting, fishing, walking (Ames *et al*. 1978)
Restoration progress	A weir has been placed on the main outflow to regulate water levels, sediment traps on several main inflows, riparian planting, spraying pest willow species, and fenced reserve margin.
Peat influence	Moderate-Low: Local wetland development
Reserve status	Recreation Reserve, administered by the Waipa District Council
Submerged vegetation	No submerged aquatic vegetation in 1992 (Champion *et al*. 1993 in Barnes, 2002)
Invasive fish	Catfish, rudd, gambusia and koi carp

2 Methods

2.1 Sampling sites

New Zealand Map Grid co-ordinates for the location of the sampling stations were determined by a handheld GPS receiver (Table 2). Figure 1 shows the locations of the inflows, outflow and three lake sampling stations.

Table 2: Abbreviations for in-lake samples sites and inflow and outflow sampling sites.

Site	Abbreviation	NZMG coordinates	
		Easting	Northing
Drain 1	D1	2711826.20	6357700.22
Drain 2	D2	2711869.12	6357754.61
Drain 3	D3	2711801.03	6358607.49
Drain 4	D4	2711861.76	6358689.17
Drain 5	D5	2711838.22	6358816.22
Drain 6	D6	2711816.74	6358835.28
Drain 7	D7	2711778.82	6358879.44
Drain 8	D8	2711720.98	6358908.70
Drain 9	D9	2711663.05	6358934.88
Drain 10	D10	2711585.61	6358961.57
Drain 11	D11	2711518.24	6359000.33
Drain 12	D12	2711479.68	6359019.83
Drain 13 (Ngarotoiti Inlet)	D13	2711170.65	6359061.80
Drain 14 (Outflow)	D14	2710737.47	6359495.52
Drain 15	D15	2710778.01	6358705.03
Drain 16	D16	2710625.96	6358585.63
Drain 17	D17	2710597.97	6358447.59
Drain 18	D18	2710737.13	6358447.06
Drain 19	D19	2710844.50	6358444.27
Drain 20	D20	2710912.05	6357942.96
Drain 21	D21	2710985.45	6357854.70
Drain 22	D22	2711311.11	6357796.90
North site	North	2711010.13	6359068.05
Middle site	Middle	2711352.34	6358372.41
South site	South	2711632.21	6357958.10

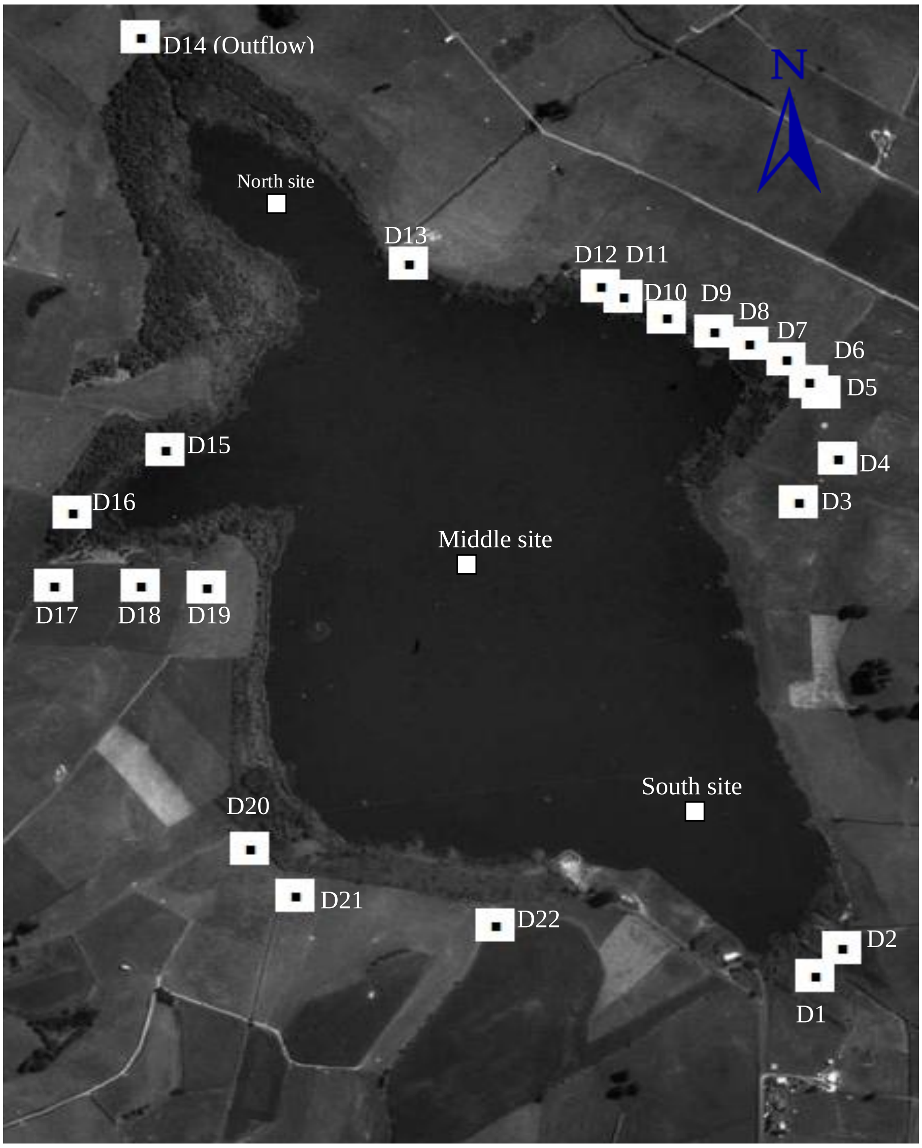

Figure 1: Aerial photograph of Lake Ngaroto showing in-lake, inflow and outflow sampling sites.

2.2 Sampling

Samples were taken approximately fortnightly on seven occasions from Mar to May 2007 (on Mar 7 and 23, April 4 and 16 and May 2, 14 and 29) (Appendix 1). On each occasion, sampling was undertaken on the lake, and on all inflows and the outflow. Waipa District Council provided flow and nutrient data from samples taken from the major inflows (D1, 2 and 13) and the outflow on dates from Aug to Sept 2007. Samples collected from Aug to Sept 2007 were analysed for nutrients (TP, NH_4, NO_3) by Hill Laboratories (Appendix 2).

Details of sampling and analytical methodology for flow and water quality data (collected 7 Mar to 29 May 2007) are presented below.

2.2.1 Lake

Water samples were collected with a Schindler-Patalas trap at three sites (Fig. 1). Samples from sites in the south and in the north were collected from depths of 0 and 1.5 m and in the mid-lake site at depths of 0, 1.5 and 3.0 m. Duplicate samples were taken only at the mid-lake site.

Samples for filterable nutrients were filtered immediately after sampling using 0.45 µm GF/C filters in a filter holder and syringe, placed on ice in the dark for transportation, and frozen upon return to the laboratory. The filter papers were also placed on ice in the dark for transportation, and then frozen in the laboratory for subsequent analysis of chlorophyll *a* concentrations. Water samples for analysis of total phosphorus (TP) and total nitrogen (TN) were also collected, placed on ice and frozen. Samples for suspended solids (SS) analysis were stored in a 500 mL reagent bottle and placed on ice until analysis on the day after sampling.

Conductivity, pH, dissolved oxygen concentration and temperature were measured at 1 m depth intervals at the mid-lake sampling site, using a Yellow Springs Instruments 6000 Multi-Parameter Sonde. Water column profiles of conductivity, temperature and depth were taken at the mid-lake sampling site with a Sea Bird Electronics 19plus SEACAT Profiler (Sea-Bird Electronics Inc., Washington). Simultaneously, additional mounted sensors on the profiler measured dissolved oxygen concentration (Sea-Bird Electronics, Inc.) and photosynthetically-available radiation (PAR, Licor Inc.).

Temperature was logged at half-hour intervals on loggers (Optic StowAway-Temp) installed at the mid-lake sampling site at depths of 0, 1.5 and 3 m on 19 December 2006 and downloaded on 29 May 2007, a period of 162 days. For the model, only data from midday are used, since this was defined as the time of model output.

2.2.2 Inflow and outflow

Samples were collected at only seven inflow sampling stations (D5, D13, D16, D17, D20, D21, D22), though there are 21 inflows in total. Only D13 had detectable discharge over the sample period. The other drains were minor and likely contribute inflows only when the catchment is relatively saturated over winter. The outflow had a detectable flow on each sample day.

All major flows were gauged using a Flow Mate flow meter on each sample day when stream flow was evident. Conductivity, pH, dissolved oxygen concentration and temperature were measured in the inflows using a Yellow Springs Instruments Sonde (see 2.2.1). Water samples were collected from the drains for analysis of concentrations of NH_4-N, NO_3-N, NO_2-N, PO_4-P, TP, TN, and SS using the same collection methods as described above for water column sampling.

2.3 Analytical techniques

2.3.1 Light attenuation coefficient

Coefficients for attenuation of PAR (k_d) were derived assuming Beer's Law attenuation, after removing the uppermost 0.5 m readings from the profile. The value of k_d was computed as the slope of the regression line of the natural logarithm of PAR plotted against depth.

2.3.2 Nutrient analysis

The water samples were analysed for NH_4-N, total oxidised nitrogen (TON), NO_3-N, NO_2-N, PO_4-P, TP, TN on a Lachat QuickChem® Flow Injection Analyser (FIA+ 8000 Series, Zellweger Analytics, Inc.). Ammonium (NH_4-N) was analysed using Lachat QuickChem® Method 10-107-06-2-C. Soluble reactive phosphorus (PO_4-P) was analysed using Lachat QuickChem® Method 10-115-01-1-A. Total oxidised nitrogen species (NO_X) and nitrite (NO_2) were analysed separately using Lachat QuickChem® Method 10-107-04-1-A, where nitrate is reduced to nitrite by passing the sample through a copperised cadmium column. Nitrate (NO_3) was subsequently determined by subtraction of NO_2 from NO_X. Water samples for TP and TN analysis were digested using a persulphate digestion method (Ebina *et al*. 1983) before analysis on the FIA as for SRP and NO_X, respectively.

Deionised water (>16 MΩ resistance) was used for preparation of standards and reagents for nutrient analysis. To avoid contamination, deionised water was obtained daily. Stock standard solutions were prepared from analytical reagent-grade chemicals, pre-dried at 105 ºC for one hour, and deionised water. These stock solutions were stored in glass bottles at 4 ºC in a refrigerator. Working standard solutions were prepared daily from serial dilutions of stock solutions with deionised water.

Laboratory reagent water blanks were analysed to demonstrate freedom from contamination. Each blank was subjected to the same procedural steps as the samples. Ongoing precision and recovery were verified using a mid-range calibration standard every ten samples or every analytical batch.

2.3.3 Chlorophyll a analysis

Chlorophyll *a* concentration was determined by pigment extraction from the thawed filters using 90 % acetone, with the aid of a mechanical tissue grinder (Arar & Collins, 1997). Fluorescence of the acetone extract was measured on a 10-AU Fluorometer (Turner Designs). Sensitive calibration factors, determined previously on solutions of pure chlorophyll *a* of known concentration, were used to calculate the concentration of chlorophyll *a* in the sample extract:

$$C_{E,c} = F_s (r / r - 1)(R_b - R_a) \qquad (1)$$

where $C_{E,c}$ is the chlorophyll *a* concentration (µg L^{-1}) in the extract solution, F_s is the response factor for the sensitivity setting, r is the before-to-after acidification ratio of a pure chlorophyll *a* solution, R_b is the fluorescence of the sample extract before acidification and R_a is the fluorescence of the sample extract after acidification.

Concentration of chlorophyll *a* in the whole water sample is reported in µg L^{-1}:

$$C_{s,c} = \frac{C_{E,c} \times extract \quad volume \times DF}{sample \quad volume} \qquad (2)$$

where $C_{s,c}$ is the chlorophyll *a* concentration (µg L^{-1}) in the whole water sample, DF is the dilution factor, and extract volume is the volume (L) of extract prepared before dilution.

2.3.4 Suspended solids

Suspended solids and particulate inorganic matter (PIM) were analysed in duplicate using filtration of samples with pre-combusted (550 °C) and pre-weighed filters (0.45 µm GF/C). Filters were then dried at 105 °C for at least 1 h in an oven and cooled in a desiccator. The cycle of drying, cooling and weighing was repeated until a constant filter weight was obtained or until the weight change was less than 4% or 0.5 mg of the previous weight. Suspended solid concentrations as total particulate matter (TPM) were determined through change in filter weight and the volume of water filtered. Filters were then combusted at 550°C for 4h to determine PIM. Particulate organic matter (POM) was determined as the difference between TPM and PIM.

2.3.5 Phytoplankton

Prior to analysis, phytoplankton samples were inverted 12 times for 30 seconds to ensure an even distribution of cells. One millilitre of sample was taken from the centre of the container using a clean pipette, and transferred slowly to a Utermöhl chamber where additional Lugol's iodine solution was added to aid settling. The samples were then left to settle for several hours before examination with an Olympus inverted microscope. An initial cell count was undertaken over the central transect area of the chamber under 400x magnification for common species, with a subsequent count over the entire chamber area under 200x magnification for less common species. Calculations of the density (cells mL^{-1}) of the sample were based upon sample volume; chamber and central transect area.

2.4 Model DYRESM-CAEDYM

DYRESM (DYnamic REServoir Simulation Model) is a one-dimensional model which simulates the vertical distribution of temperature, salinity and density. A horizontal layer structure is the foundation for DYRESM and this structure changes according to heat, mass and momentum exchanges (Imberger & Patterson, 1981; Gal *et al*. 2003). A coupled ecological model, CAEDYM (Computational Aquatic Ecosystem DYnamics Model), is used to simulate phytoplankton biomass, DO, nitrogen, phosphorus and carbon, using partial differential equations that utilise rate constants (Robson and Hamilton, 2004) which are varied by the modeller and maintained within limits considered realistic for the ecological rates that they attempt to simulate (Appendix 3). Sediments on the lake bottom are a repository for particulate matter and act in the model as a source of dissolved nutrients generated in the model according to the physical nature of the water column, as well as particulate matter based on shear stress, which is in turn a function of lake morphology and wind speed. The DYRESM-CAEDYM model was run with daily input data, including inflows, outflows and meteorology, from 19 Dec 2006 to 18 Dec 2007, with daily input data for inflow and outflow.

2.4.1 Meteorological data

Daily meteorological data (Fig. 2) required as input to the DYRESM-CAEDYM model were taken from the Hamilton Aero (Hamilton Airport) and Te Awamutu (Paepaerahi) weather stations. The data sets for cloud cover (CC) and air pressure (es), wind speed (u_0), solar radiation (SW - shortwave), air temperature (Tair) and relative humidity were taken from Hamilton Aero; the data for rain (m) was taken from Paepaerahi. Daily averages were determined for all meteorological data except rainfall for which the sum a daily rainfall value was used.

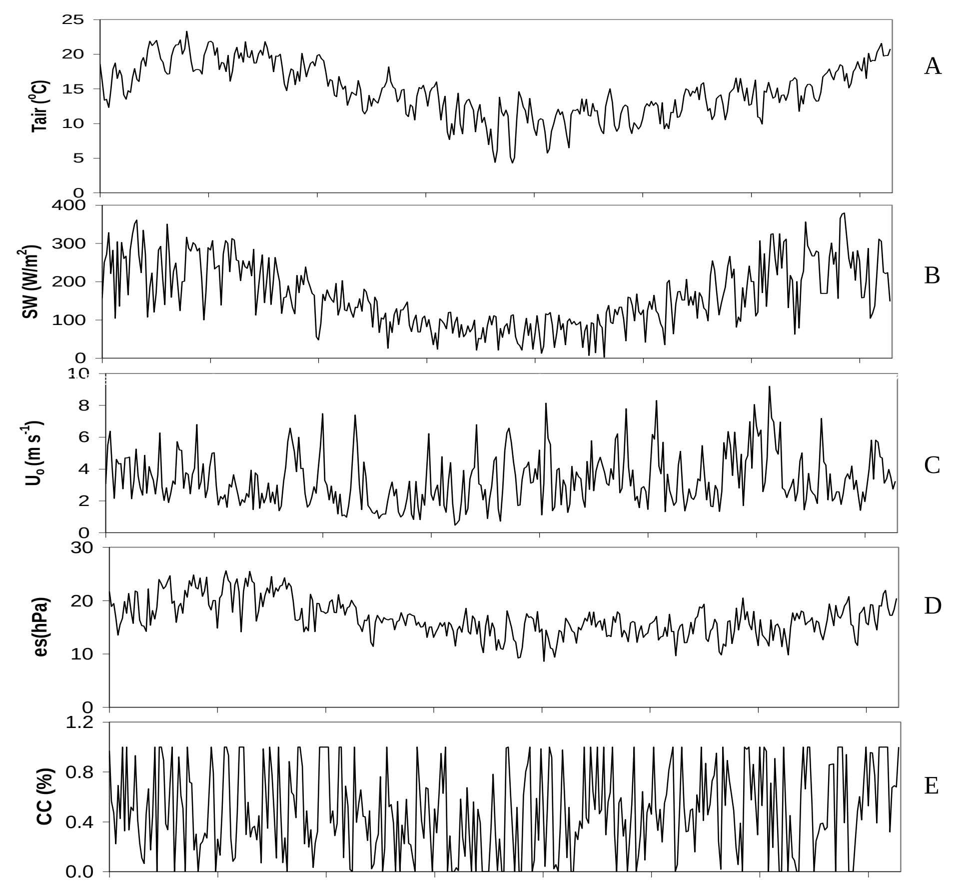

Figure 2: Meteorological data used as input to the DYRESM model, including (A) air temperature Tair (°C), (B) short wave radiation (SW), (C) surface wind speed (u_0), (D) vapour pressure (es) and (E) cloud cover (CC).

2.4.2 Water balance

Change in lake water storage (ΔS) was calculated from water level data provided by Environment Waikato and adjusting for the lake area. There was data missing from 4 Aug to 13 Oct 2006 so data from the same period in 2007 was inserted as a surrogate.

The combination of water balance equations for the catchment and for the lake was used to resolve the values for the different components of the lake water balance.

Inflow from the catchment was calculated using:

Inflow=Rainfall on catchment - Evaporation from catchment. (3)

Evaporation from the catchment was estimated from wind speed, since wind speed was significantly correlated with evaporation from the lake ($p<0.01$, $r=0.92$, $N=365$; Fig. 3). The remaining rainfall volume was then used as the model inflow, where groundwater inflow and surface inflow were combined. To rectify any numerical problems of negative inflow values it was necessary to use 21-day averaged for the rainfall and evaporation data.

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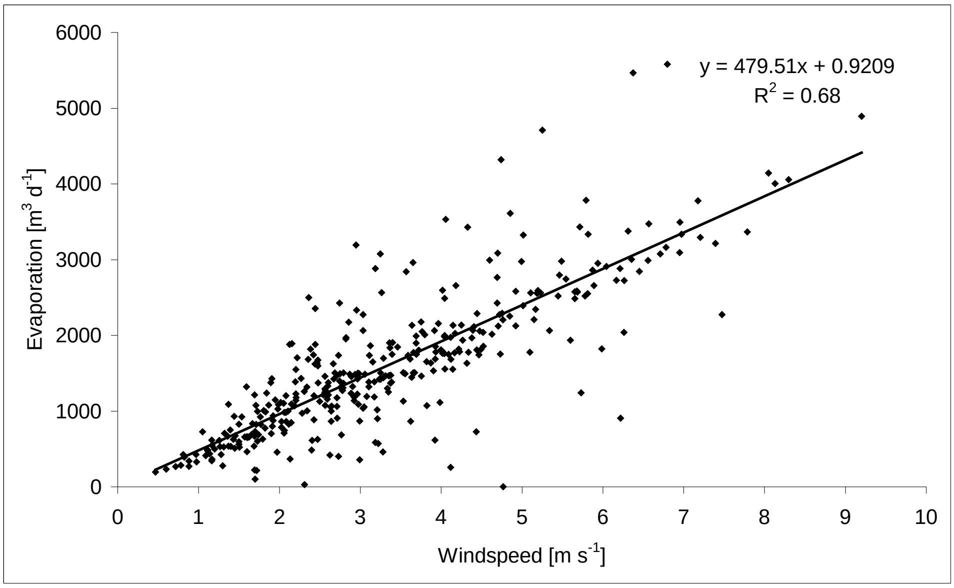

Figure 3: Lake evaporation vs wind speed.

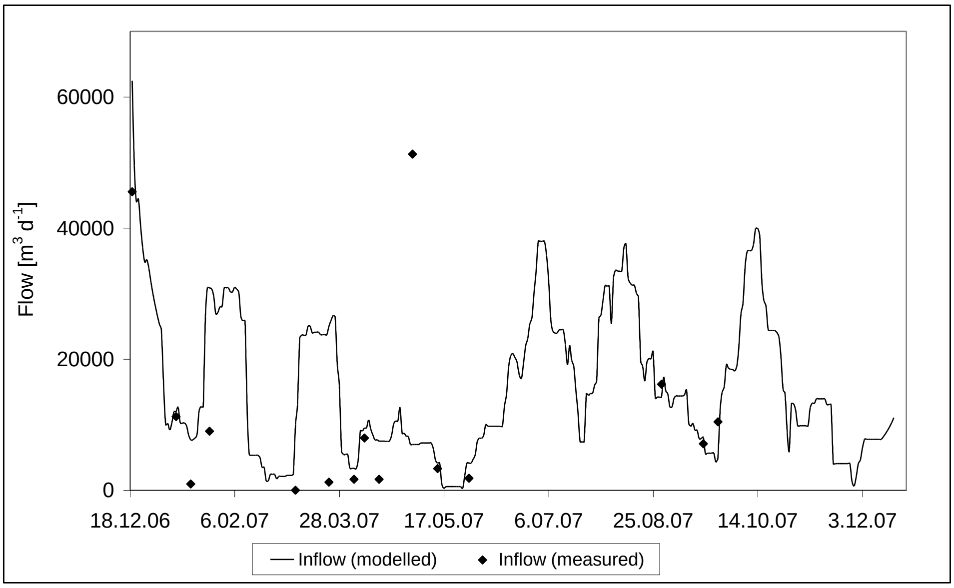

Figure 4: Measured and modelled total inflows to Lake Ngaroto.

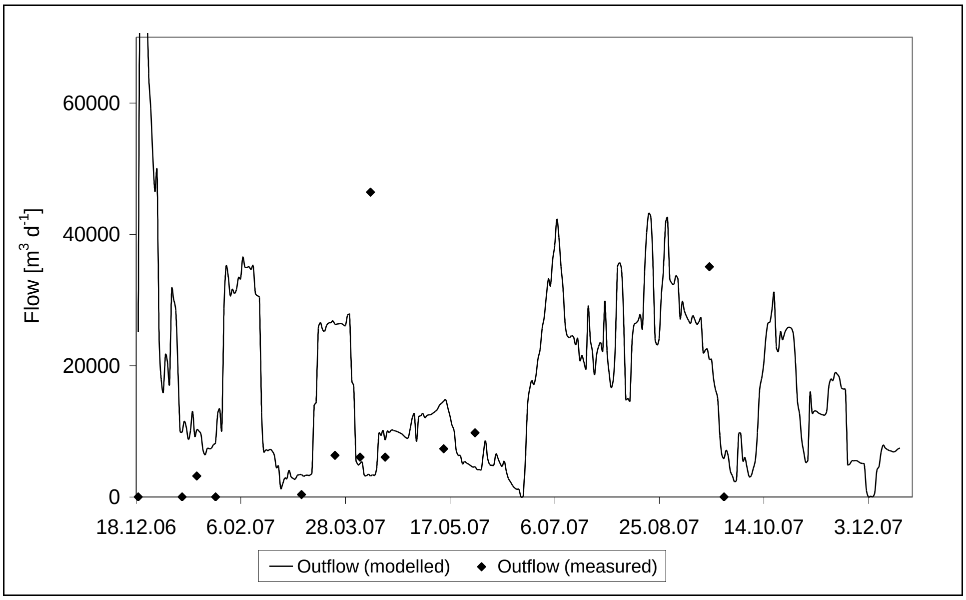

Figure 5: Measured and modelled outflow from Lake Ngaroto.

The change in storage over time, $\Delta S/\Delta t$, was calculated by setting the highest recorded water level to a water depth (z) of 3.5 m. Surface areas (A) for each recorded water level were calculated using the changes in morphometry according to the hypsography of the lake. The change in volume was then calculated as $\Delta A/\Delta z$, where ΔA is difference in area in m^2 and Δz is lake depth in m.

Using calculated evaporation for the lake (Eqns 5-8) in the water balance equation (Eq. 4), the inflow (surface + groundwater) (Fig. 4) and outflow (Fig. 5) for the lake were calculated as:

$$\Delta S/\Delta t = \text{Inflows} + \text{Rainfall} - \text{Outflow} - \text{Evaporation} \qquad (4)$$

Where ΔS is change in lake storage in m^3 and Δt is difference in time in days.

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, Eq. 6.20) using data from Hamilton Aero weather station and water temperatures from the surface temperature logger (Fig. 7) at the mid-lake sampling station (Fig. 1).

$$Q_{lh} = \min\left(0 \geq \frac{0.622}{P} C_L \rho_A L_E U_a \left(e_a - e_s(T_s)\right)\Delta t\right) \qquad (5)$$

where:

Q_{lh} is the evaporative heat flux in J m^{-2} s^{-1},
P is the atmospheric pressure in hPa,
C_L is the latent heat transfer coefficient for wind speed at height 10m (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 J kg^{-1}),
U_a is the wind speed in 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 $Q_{lh} < 0$ allows for inclusion of then there is condensation on the water surface. The saturated vapour pressure $e_s(T_s)$ is calculated via the Magnus-Tetens formula (TVA 1972, Eq. 4.1):

$$e_s(T_S) = \exp\left[2.3026\left(\frac{7.5T_S}{T_S + 237.3} + 0.7858\right)\right] \qquad (6)$$

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

$$\Delta M_N^{(lh)} = \frac{-Q_{lh} A_N}{L_V} \qquad (7)$$

where:

$\Delta M_N(lh)$ is the change in mass in kg s^{-1} (assumed to be L 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}).

The result of this calculation was multiplied by 86400 s day^{-1} to produce a daily evaporation value (E_L).

2.4.3 Inflow and outflow data

Five inflows (D1, D2, D13, D16, D21) were assigned as independent inputs into the model. These inflows represented those that had been measured on any one occasion from the measured data collected between Dec 2006 and May 2007.. Of the five inflows, only one (D13) was flowing on each measurement days, while the remainder flowed intermittently. To apportion the relative daily volume to each inflow for the unmeasured days, the proportion of total inflow that each inflow represented for measured inflow days was used.

To estimate surface temperature of the inflow, a cosine model was developed from available temperature readings in the streams (Fig. 6) using the following equation:

$$T_s=A\cos(\omega t+\sigma)+T_0 \qquad (8)$$

where

T_s is the estimated water temperature in ^oC
A is the amplitude in m
ω is the angular frequency ($2\pi/365$)
σ is the phase angle
T_0 is the mean water temperature in ^oC
and t is time in days.

Quality of fit was defined by average difference between measured and modelled water temperature and the Pearson correlation coefficient (r) value. Parameters were minimised and maximised, respectively using *Microsoft Excel Solver*. Analysis of the values for parameters produced 1 x 10^{-6} for average difference between measured and modelled temperature and $r^2=0.89$.

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

$$\mathrm{DO} = \mathrm{EXP}(7.71 - 1.31 * \ell n(\mathrm{T} + 45.93)) \qquad (9)$$

where

DO is dissolved oxygen in mg L^{-1}
and T is water temperature in ^oC.

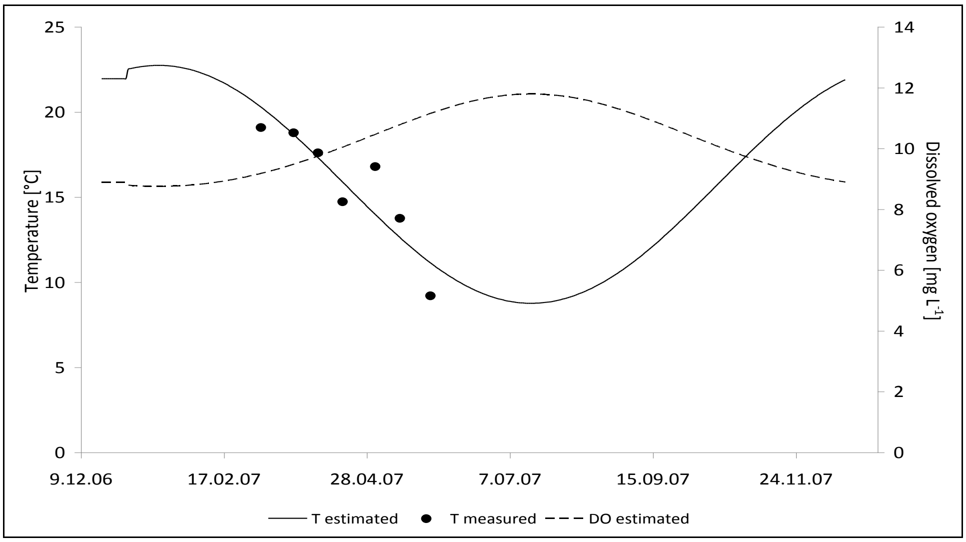

Figure 6: Measured temperature and modelled temperature and dissolved oxygen for the lake inflows.

Where there were missing values for nutrients concentrations (NH_4, NO_3, PO_4, TP, TN) the average of measured concentrations in the inflows was used.

2.4.4 Morphometry of the Lake

The morphometry of Lake Ngaroto was determined using a bathymetric map of the lake. The depth profile was prepared with 0.5 m steps and the area of each 0.5 m contour was determined from the map. The water volume for each depth was generated by multiplying the relevant area by the corresponding depth.

2.4.5 Initial profile

The depth and temperature for the initial profile were measured with a Yellow Springs Instruments 6000 Multiparameter Sonde on 19 December 2006.

2.4.6 Phytoplankton

Two phytoplankton groups, represented by equivalent chlorophyll *a* concentration, were simulated in the model. This simulation represents phytoplankton similar to diatoms and cyanobacteria, the dominant phytoplankton groups in Lake Ngaroto. Initial lake water column concentrations of Chl *a* for the phytoplankton group were determined from cell concentrations and Chl *a* concentrations at several depths.

2.4.7 Suspended solids

Two different particulate inorganic suspended solids (SSOL1 & SSOL2) and particulate inorganic phosphorus (PIP) and particulate nitrogen (PIN) have been integrated into the model because they have a significant impact in shallow lakes like Lake Ngaroto, especially on the temperature profile due through increased attenuation of light and a follow-on effect on the lake’s heat budget. The initial concentration of suspended inorganic matter was taken from the samples collected on the first day.

2.5 Model simulation of restoration scenarios

A simulation that acted as a control was first set up based on the model calibrated for the period of measured data, but extended to produce simulation output over a period of 2 years. For Scenario IV the maximum water level was 2.54 m and this depth is used as the surface sample (noted as 3 m) for comparisons with the other scenarios.

2.5.1 Scenario I

As the inflow from Lake Ngarotoiti (D13) supplies the greatest proportion of the water and nutrients flowing into the lake, a diversion of the inflow (D13) from Lake Ngarotoiti to the present outlet (D14) is simulated in this scenario.

Since flows have been combined in the inflow file for the model, D13 was diverted as follows. Measured inflows for D13 were averaged for the period 12 Dec 2006 until 25 Sept 2007. The measurement on the 02 may 2007 was omitted because this was an unusually high inflow and not considered representative for that period. The calculated average flow of 6144 $m^3\ d^{-1}$ (39% of total inflow) was then subtracted from the total inflow. Any resulting negative inflows were set to zero and considered realistic since field observations showed that on some days there were no measurable inflow. The same amount of water was subtracted from the outflow discharge, to maintain water levels the same as for the control case.

Nutrient concentrations for the inflow were recalculated as a volumetric average across measured streams but without the inflow from Lake Ngarotoiti.

2.5.2 Scenario II

Currently, the outflow (D14) of Lake Ngaroto is partially dammed by a weir gate in mid-September, to increase the level of the lake by 0.4 m. The gate is opened around 1 May each year. This scenario involved simulation of weir gate in place all year round, adding 0.4 m to the water level over the winter period (1 May to mid-Sept).

Crest elevation was set to 3.38 m which was the maximum modeled water depth and considered to be the water depth when the weir was opened. Outflow was set to zero until the desired water level was attained with the weir in place. Once the water exceeded the crest elevation (3.38 m), it would begin to overflow. The purpose of this scenario was to examine how water level might impact on sediment resuspension in Lake Ngaroto. Shallow lakes with a long fetch, such as Ngaroto, can have high levels of suspended sediment as a result of shear stress generated on the lake bottom from wind-wave action.

2.5.3 Scenario III

This scenario combined scenarios 1 (divert D 13) and 2 (increase winter water level). Measured inflows for D13 were averaged for the period 12 Dec 2006 until 25 Sep 2007 and the same procedure was followed as for Scenario I, to adjust for loss of this inflow. Similarly, water levels were adjusted as in Scenario II.

2.5.4 Scenario IV

A hypothetical scenario for Lake Ngaroto would be to convert it to a managed wetland. The minimum water level would be decreased by 0.4 m through permanent removal of the weir.

Minimum water level (modeled) was reduced by 0.4 m and crest elevation was set to 2.54 m. Outflow was set to zero flow since water in the lake would simply overflow when the water level exceeded 2.54 m. Initial water level was adjusted to 2.5 m in the initialization file of the model.

2.5.5 Scenario V

This scenario involved removal of 20 cm of sediment from the entire bottom of the lake thus deepening the lake and also changing the nature of the bed sediments that resupply sediment and nutrients to the water column.

It was assumed that changes in vertical distributions of bioavailable phosphorus would similar to those of TP. TP concentrations in the sediment have been found to be 15.7 % less at 20 cm depth than in the surface sediment. Release rate of PO_4 in the model was therefore reduced by 15.7%. Phosphate concentrations in the sediment have been found to be 62.5% less at 20 cm depth than in the surface sediment. In this case the PO_4 release rate in the model is reduced by 62.5%. The ammonium concentrations in the sediment at 20 cm depth have been found to be 273% of the concentration found in the surface sediment. The release rate of NH_4 in the model was adjusted accordingly. Whether the sediment would sustain that release rate is uncertain. However, we are simulating only a short period and immediate effects should be visible. Two different release rates were modeled and are compared with Faithfull *et al*. (2005) in Table 3.

Table 3: Release rates (g $m^{-2}d^{-1}$) **for PO_4 and NH_4 from the sediment for Sc V compared to model and Faithfull *et al*. (2005)**

	(Faithfull *et al*. 2005)	**Model (calibrated)**	**(Sc V-1)**	**(Sc V-2)**
PO_4	0.001	0.02	0.008	0.017
NH_4	0.077	0.05	0.14	0.14

To deepen the lake, changes in the morphometry were made according to the hypsography.

Comment [DH2]: Sorry, I am lost. Can't work this out. Also was 20 cm added on, or was the deepest point deepened.

2.5.6 Scenario VI

The land use composition of the Lake Ngaroto catchment is 81.1% dairy pasture, 15.5% drystock pasture and 3.4% other types (Jenkins & Vant, 2006). Using average values for nutrient losses in the Waikato region for different land uses (Ledgard and Power 2006, Meneer *et al*. 2004), total export from dairy pasture for the catchment is estimated to be 51.1 t N yr^{-1} and 0.71 t P yr^{-1} and from dry stock, 3.51 t N yr^{-1} and 0.08 t P yr^{-1}. A change of land use from dairying for the catchments of inflows D1 and D2 (about one-third of the catchment) with reduction of the present nutrient inflow by 33.3% in option 1 and by 50 % in option 2 of of the scenario.

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Nutrient concentrations in the model inflow were reduced by 33% (Scenario VI 33%) and by 50% (Scenario VI 50%).

2.5.7 Scenario VII

This scenario involved adjustments to the model to provide an equivalent effect of installation of two wind barriers installed across the lake, cutting off the bays at the south and north ends of the lake and leaving a ~500 m stretch in the middle of the lake between the barriers. The objective of this scenario was to examine the effect of actions that may lead to a reduction in shear stress resulting from wave action.

Using a sediment resuspension model developed by Hamilton & Mitchell (1996) it was determined that reduction of wind speed by 50% decreased the benthic shear stress by about the same amount as reducing the fetch by 50%. Therefore, for this scenario, the wind speed was reduced by 50% in the meteorological file.

3 Results

3.1 Flow results

Results from the monitoring program from 7 Mar 2007 to 29 May 2007 (Appendix 1) include inflows D1, D5, D13, D16, D17, D20, D21, D22 (Fig. 1) and the outflow (D14). The inflow peaked at 51,259 m³ d^{-1} in D13 on 2 May 2007. Inflow D13, arising from Lake Ngarotoiti, was the dominant inflow to the lake (Fig. 1). The observed outflow ranged from 363.1 m³ d^{-1} on 7 Mar 2007 to 189,511 m³ d^{-1} on 2 May 2007.

3.1.1 Temperature, dissolved oxygen, pH and conductivity

Averaged temperature for the measured inflows decreased from 7 Mar 2007 to 29 May 2007, from 18.4°C to 9.2°C, coinciding with reductions in air temperature during this period. DO concentrations ranged between 2.26 mg L^{-1} on 14 May 2007 in D13 to 12.94 mg L^{-1} (supersaturated) on 29 May 2007 in D21. Generally, DO was between 5 mg L^{-1} and 10 mg L^{-1} in all inflows and in the outflow. Measurements of pH in the inflows were in the range 5.91 - 7.38 while in the outflow the range was 7.0 - 7.7 except for 7 March 2007 when it was 6.56. The pH in the outflow reflected the generally higher pH of the lake. Conductivity was generally <100 mS cm^{-1} and varied strongly during the monitoring period. The highest conductivity was recorded on 2 May 2007, with 290 µS cm^{-1} in D17 the highest of the inflows.

3.1.2 Nutrients

Concentrations of TP in D16, D17, D20, and D21 were consistently <0.1 mg L^{-1}. The TP concentrations in D5 were slightly greater than 0.1 mg L^{-1}, with highest concentrations of 0.13 mg L^{-1} on 16 April and 2 May 2007. Inflow D13 (from Ngarotoiti) generally had highest levels of TP of around 0.1 mg L^{-1} except on the first sample day when it was 0.03 mg L^{-1}. The peak concentration in D13 was 0.27 mg L^{-1} on 2 May 2007. In inflow D22, TP was up to 0.30 mg L^{-1} during the first four sample days but it then decreased to <0.1 mg L^{-1} for remaining sample days The highest TP concentration in the outflow was 0.19 mg L^{-1} on 2 May 2007 but <0.1 mg L^{-1} on the other days. Concentrations of PO_4-P were consistently <0.05 mg L^{-1} apart from on 2 May 2007 when, for example, a concentration of 0.05 mg L^{-1} was recorded in inflow D21. The outflow concentrations of PO_4-P were similar to those of the lake and were generally <0.02 mg L^{-1}.

Concentrations of TN were mostly in the range 0.5-1.5 mg L^{-1} but D13, in particular, had consistently high concentrations of TN of over 1.34 mg L^{-1}. It was also notable that TN in all inflows peaked on 2 May 2007 with concentrations > 2.5 mg L^{-1} in all inflows except D22 (1.96 mg L^{-1}). The highest concentration on that day was 3.75 mg L^{-1} in inflow D21. The concentrations of TN in the outflow reflected the concentrations of the lake and were in the range 0.69-1.86 mg L^{-1}. Concentrations of NH_4-N in D16, D20, D21 and D22 were consistently <0.1 mg L^{-1} with the exception of 0.14 mg L^{-1} in D21 on 2 May 2007. The concentrations in D5 varied from 0.05 mg L^{-1} to 0.16 mg L^{-1}. For inflow D13, NH_4-N was >0.25 mg L^{-1} except on 16 Apr 2007 when it was 0.04 mg L^{-1}. Highest concentrations of NH_4-N were observed in D13 on 14 May 2007 at 0.34 mg L^{-1}. The measured values in the outflow were consistently less than 0.04 mg L^{-1} and well below the inflow concentrations. Concentrations of NO_3-N in the inflows peaked on 2 May 2007 at >1.20 mg L^{-1}. On the other sample days NO_3-N was generally <0.2 mg L^{-1}. Exceptions were for inflow D13 with concentrations consistently <0.45 mg L^{-1} and for inflow D21 with concentrations around 0.3 mg L^{-1} but excluding 7 Mar 2007 when the concentration was 0.05 mg L^{-1}. Concentrations of NO_3-N in the outflow were <0.15 mg L^{-1} except on 7 March 2007 when the concentration was 0.3 mg L^{-1}.

3.1.3 Chlorophyll a

Chl *a* concentrations in inflows D5, D16, D17, D20 and D21 were consistently <5 µg L^{-1}. A high Chl *a* concentration (113.8 µgL^{-1}) occurred in inflow D13 on 2 May 2007. Chl *a* in D22 was consistently >30 µg L^{-1} with concentrations up to 44 µg L^{-1} on 7 Mar 2007. The Chl *a* concentration in the outflow varied from 3.6 µg L^{-1} on 16 Apr 2007 to >40 µg L^{-1} on 2, 14 and 29 May 2007.

3.1.4 Suspended solids

SS ranged from < 2 mg L^{-1} up to 43 mg L^{-1} in D5 on 07 March 07. With the exception of sites D13 and D22, SS concentrations i all other inflows peaked on 7 Mar 2007. Concentrations of suspended solids in the outflow were highest (50 mg L^{-1}) on 7 Mar 2007.

3.2 Lake Results

3.2.1 Temperature, dissolved oxygen, pH and conductivity

Water samples from the lake surface at three stations (north, middle and south), and two samples from the mid-lake station, at 1.5 and 3.5 m depth were used to determine nutrient, Chl *a* and suspended solids concentrations in Lake Ngaroto, In addition, temperature, dissolved oxygen, pH and conductivity were recorded at the mid-lake station. The surface water temperature on 5 Mar 2007 was the highest recorded during the monitoring period, at 23.6 °C. The temperature decreased to an average of 14.2 °C on the last sample day, 29 May 2007.

Concentrations of dissolved oxygen in the water column were generally >7.5 mg L^{-1} except for a recorded value of 3.55 mg L^{-1} at a depth of 3.0 m on 7 Mar 2007. The peak DO concentration of 11.90 mg L^{-1} was recorded at the surface on 14 May 2007.

The pH ranged between 7.16 on 2 May 2007 at a depth of 3.0 m and 8.72 on 23 Mar 2007 at the surface. Values decreased consistently with depth so that the pH average at the surface was 8.06, 7.82 and 7.47 at the surface, 1.5 m and 3 m depth, respectively.

Conductivity averaged 146 µS cm^{-1} for all samples and varied little with depth. The highest conductivity reading was 167 µS cm^{-1} on 7 Mar 2007 at the surface and the lowest was 134 µS cm^{-1} on 29 May 07 for all three measurements depths (0, 1.5 and 3 m).

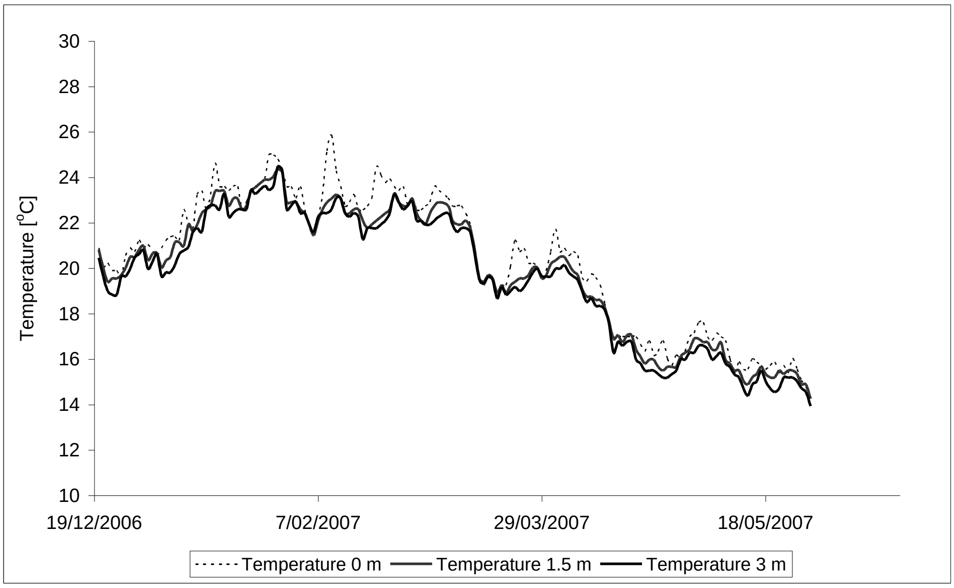

Figure 7: Daily averages of three depths (0, 1.5 and 3m) of water temperature for the mid-lake station of Lake Ngaroto for the period 19 December 2006 to 29 May 2007.

3.2.2 Nutrients

Concentrations of TP in Lake Ngaroto averaged 0.13 mg L^{-1} over all sites and all depths. There were no evidence of differences between the middle, north and south sampling sites. The lowest TP of 0.09 mg L^{-1} occurred at the southern lake station on 14 May 2007. Concentrations of PO_4-P in the lake ranged between 0.003 and 0.02 mg L^{-1}, apart two samples taken on the last two days from the southern lake station, with concentrations of 0.03 mg L^{-1} on 14 May 2007 and 0.04 mg L^{-1} on 29 May 2007.

TN in the lake was consistently around 1 mg L^{-1} except 7 Mar 07 when the concentrations in the middle of the lake at the surface and in 1.5m were found to be 1.38 mg L^{-1} and 1.34 mg L^{-1} respectively. NH_4–N in the lake was around an average of 0.16 mg L^{-1}.The highest concentration was 0.04 mg L^{-1} at the mid-lake site at 1.5m depth on 2 May 07. Low concentrations, generally <0.01 mg L^{-1} were observed at every site except in the north of the lake on 29 May 07. NO_3–N was generally under 0.01 mg L^{-1} and peaked at all sites on 02 May 07 with concentrations up to 0.1 mg L^{-1}.

3.2.3 Chlorophyll a

Chl *a* concentrations at the three sample sites ranged from 10 to 54 µg L^{-1} over the entire study period. There was a noticeable increase in the Chl *a* concentration on 29 May 2007, with values up to 53.60 µg L^{-1} at the middle site at a depth of 1.5m.

3.2.4 Suspended solids

Concentrations of SS varied from <2 mg L^{-1} to >50 mg L^{-1}. On the first sample day concentrations were generally highest, with concentrations for some samples exceeding 50 mg L^{-1}.

3.2.5 Light attenuation coefficient (k_d) and Secchi depth

The light attenuation coefficient (k_d) ranged between 3.9 and 5.4 m^{-1} (Table 4). Secchi depths were lower in Mar and Apr 2006 (0.3 - 0.39 m) but increased in May (0.41 – 0.5 m) across the three stations.

Table 4: K_d [m^{-1}] and Secchi depth [m] for Lake Ngaroto at the mid-lake station, 7 March to 29 May 2007.

Date	7/3/2007	23/3/2007	4/4/2007	6/4/2007	2/5/2007	14/5/2007	29/5/2007
K_d-Value	4.85	4.72	4.6	5.4	4.0	3.88	4.72
Secchi depth	0.3	0.39	0.32	0.31	0.48	0.5	0.41

3.2.6 Phytoplankton

The most common phytoplankton groups collected on sample days were cyanobacteria and diatoms. Most dominant of the cyanobacteria was the species *Microcystis wesenbergii*, which peaked on the 23 Mar 2007 with a density of 28,507 cells mL^{-1}. The dominant diatom was *Aulacoseira granulata* var. *angustissima spiralis* with an average concentration of 17,191 cells mL^{-1} (83 % of the observed diatoms). Figure 8 shows the relative abundance of cyanoabcteria, diatoms and, collectively, other phytoplankton.

The species *Aulacoseira granulata* (diatom), *Pediastrum* sp. (chlorophyte), *Peridinium* sp. (dinoflagellate) and *Trachelomonas* sp. (euglenophyte). *Pediastrum* sp., *Peridinium* sp. and *Trachelomonas* sp. were present in almost all water samples through the study period.

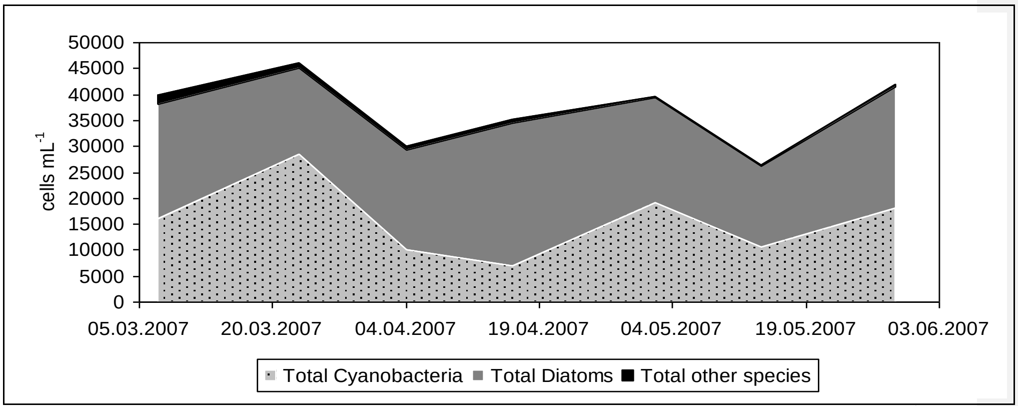

Figure 8: Phytoplankton densities for cyanobacteria, diatoms and total other species (cells mL^{-1}) for the mid-lake station, 7 March to 29 May 2007**.**

3.3 Model results

As the field data that the model was calibrated against was only measured from Dec 2006 to May 2007 and the modelled data was from Dec 2006 to Dec 2007, statistical analyses for relationships between the two were not performed. The figures below provide a visual comparison of the closeness of fit between the model and measurements.

3.3.1 Temperature

The simulated temperature of Lake Ngaroto showed consistently a fully mixed water column over the whole study period with a ranged from 25.5 ^{o}C in February to 7.5 ^{o}C in June (Fig. 9) consistent with the measured water temperatures (Fig. 7) and roughly tracking air temperature (Fig. 2). The difference between simulated and measured values is generally < 1 ^{o}C.

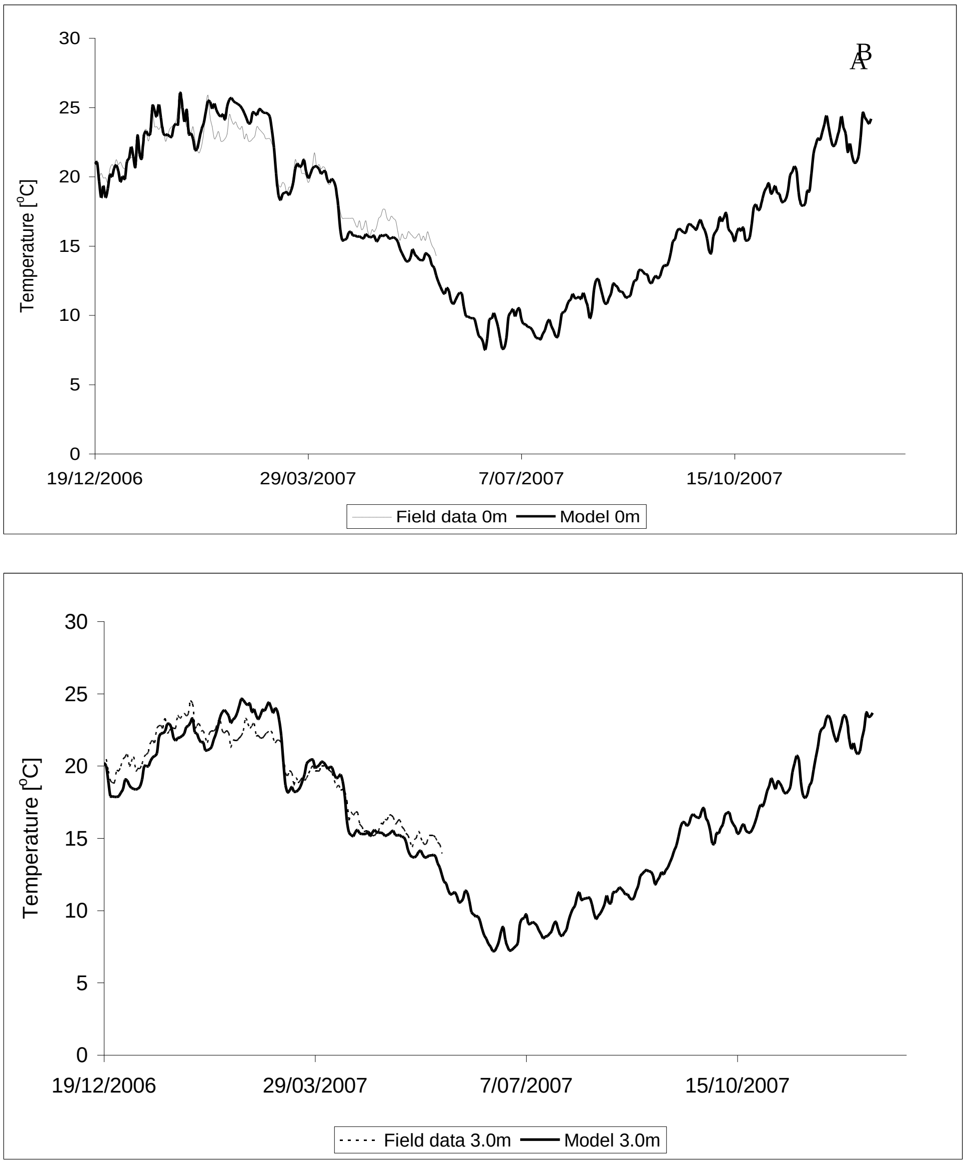

Figure 9: (A) Surface, (B) bottom [3.0m] water temperatures in Lake Ngaroto derived from model simulations, and field measurements, for the period 19 Dec 2006 to 18 Dec 2007.

3.3.2 Dissolved oxygen

The simulation of dissolved oxygen in the water column of Lake Ngaroto shows a concentration difference of c. 2 mg L^{-1} between the surface and 3 m depths over the period December and March (Fig. 10). From Mar-Dec 2007, there is very little difference between the concentrations at both depths. The simulation results have dissolved oxygen concentrations at the beginning of the simulation (19 December 2006) of around 9 mg L^{-1} after which the concentration steadily decreases to as low as 2.9 mg L^{-1} at the 3 m depth in mid-March and 6.6 mg L^{-1} in the surface waters at the same time.. In March the modelled dissolved oxygen concentration increased sharply to c. 9 mg L^{-1} then increased with some fluctuations to a peak concentration of 11.0 mg L^{-1} in July before decreasing to approximately 7 mg L^{-1} in December. Although the simulated DO concentrations followed a similar pattern to the field measurements the simulated data was about 1-2 mg L^{-1} greater than field measurements up until mid-March then 1-2 mg L^{-1} less than field measurements between March and May. In general, however, the discrepancies were considered acceptable, especially given the fixed time of model output (midday) compared with sampling times (variable).

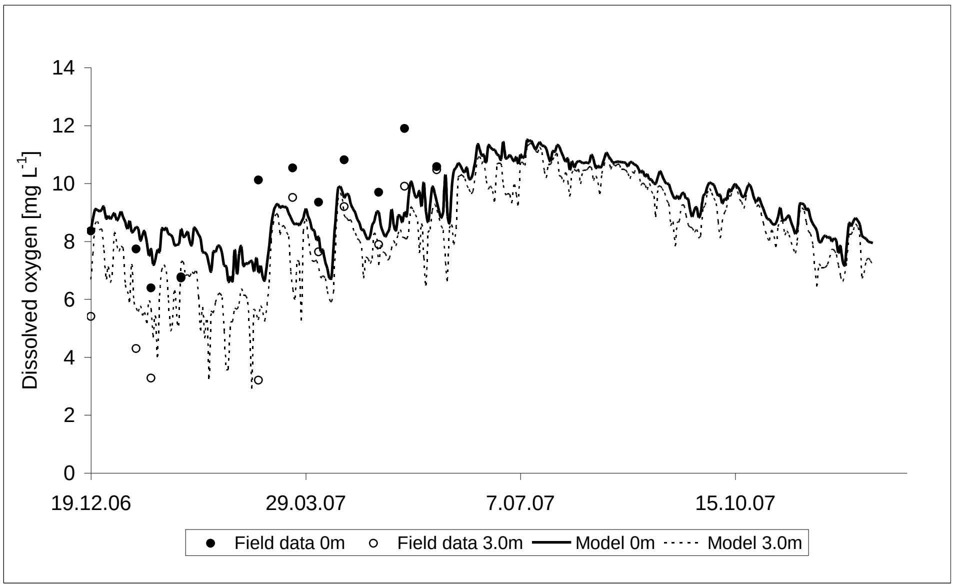

Figure 10: Dissolved oxygen concentrations in Lake Ngaroto at the surface and 3 m depths derived from model simulations, and field measurements, for the period 19 Dec 2006 to 18 Dec 2007.

3.3.3 Nutrients

Modelled results for TP (Fig. 11) are generally lower than the field measurements, while in the measurements the 3 m depth concentrations tend to be higher than surface water concentrations. Measured data ranged from 0.21 mg L^{-1} in Jan 2006 to 0.028 mg L^{-1} in May 2006 while simulated data ranged from 0.16 mg L^{-1} in Dec 2006 to 0.05 mg L^{-1} in Sep 2006, with an overall trend of decreasing concentration.

TN concentrations (Fig. 12) are greater than the simulated results for Jan 2006 and lower in Apr and May 2006. The model results showed relatively modest changes through time.

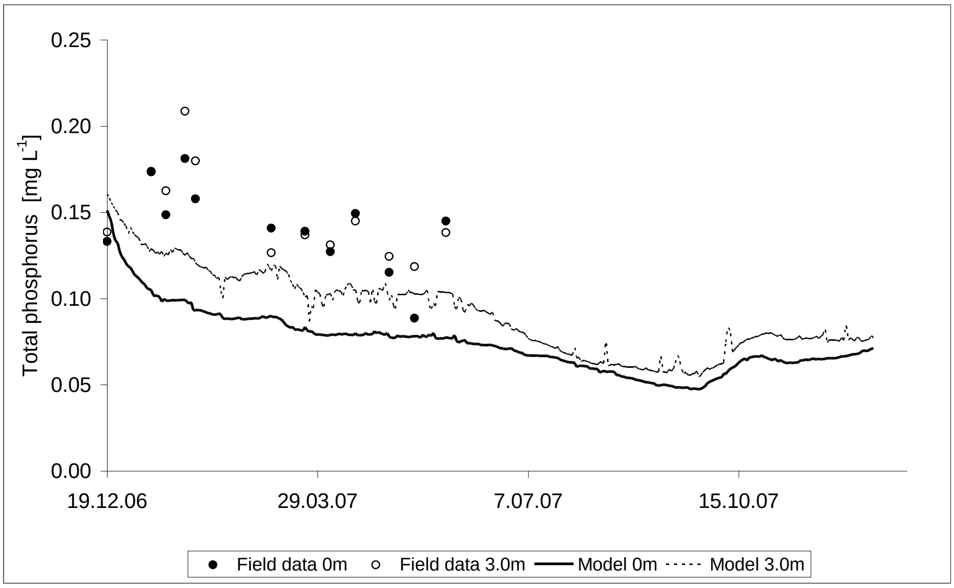

Figure 11: Total phosphorus concentrations in Lake Ngaroto at the surface and 3 m depths derived from model simulations, and field measurements, for the period 19 Dec 2006 to 18 Dec 2007.

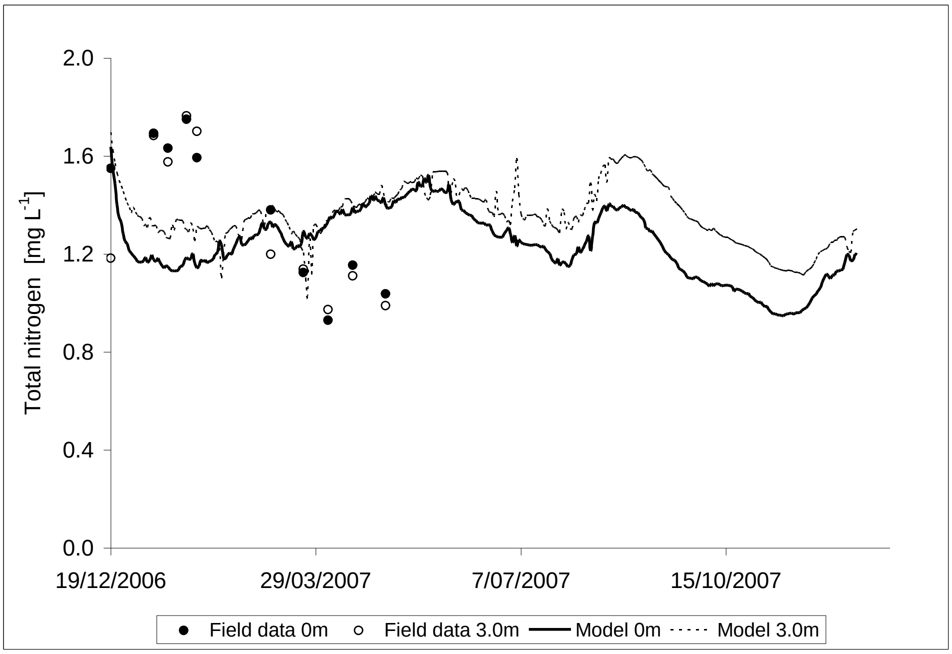

Figure 12: Total nitrogen concentrations in Lake Ngaroto at the surface and 3.0 m depths derived from model simulations, and field measurements, for the period 19 Dec 2006 to 18 Dec 2007.

3.3.4 *Chlorophyll a*

Simulated Chl *a* concentrations were mostly similar to the observations but did not tend to capture the high variability, particularly some of the very low concentrations in surface waters at between Dec and July 2006 (Fig. 13). Generally, modelled Chl *a* concentrations tended to be a little higher than the field data for surface waters but similar for the 3 m depth. The modelled concentrations for surface and bottom waters for July to Nov 2006 matched more closely.

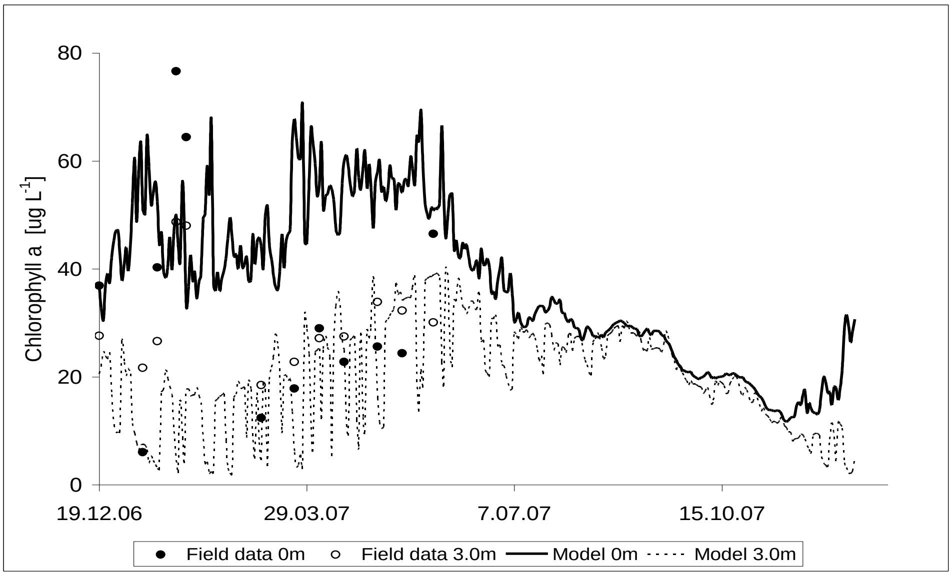

Figure 13: Chlorophyll *a* concentrations in Lake Ngaroto at the surface and 3.0 m depths derived from model simulations, and field measurements, for the period 19 Dec 2006 to 18 Dec 2007.

3.3.5 *Suspended solids*

In Figure 14 modelled results for SS differ considerably from the field data. In the field data, there are high concentrations between Jan and May 2006 with a peak of 51 mg L^{-1} in Mar. The peak SS concentration of 61 mg L^{-1} for the simulation occurred in Oct 2006. Lowest measured concentrations occurred in May.

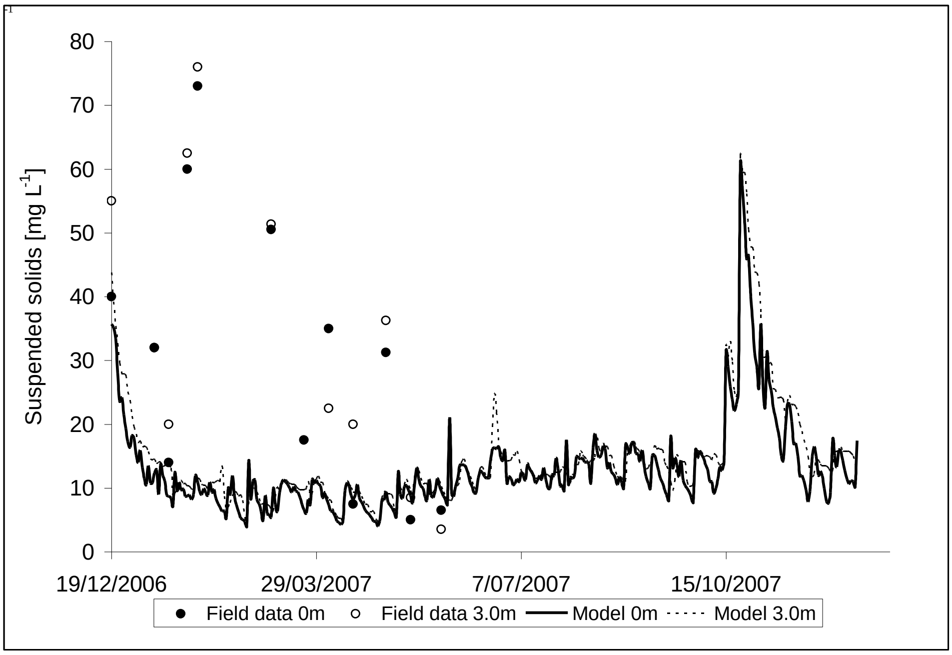

Figure 14: Suspended solid concentrations in Lake Ngaroto at the surface and 3.0 m depths derived from model simulations, and field measurements, for the period 19 Dec 2006 to 18 Dec 2007.

3.4 Restoration scenario results

3.4.1 Scenario I (Ngarotoiti diversion)

When the inflow from Lake Ngarotoiti (D13) was diverted from Lake Ngarotoiti to the present outlet (D14), DO remained similar to the control at 0 and 3 m depths for both years (Figs 15, 16), TP remained similar to the control at 0 and 3 m depths for the first year then was lower than the control in the second year at both depths (Figs 17, 18), TN was similar to the control for Dec to Mar 2006 and was then greater than the control from Mar to Sept 2006 and less than the control for Sep 2006 to Mar 2007 at 0 and 3 m depths (Fig. 19,20); Chl *a* was generally similar to the control at 0 and 3 m depths for both years with the exception of the period from Sep 2006 to Dec 2007 when concentrations for Scenario I were less than the control (Figs 21,22). Concentrations of SS were similar to the control at 0 and 3 m depths for both years (Figs 23 and 24).

3.4.2 Scenario II (permanent weir)

When the outflow (D14) was dammed by a permament weir gate, adding 0.4 m to the water level over the winter period (1 May to mid-Sep 2006) DO remained similar to the control at 0 m depth for both years but was slightly higher than the control during the winter months at 3 m depth (Figs 15, 16), TP remained similar to the control at 0 and 3 m depths for the first year with the exception of the period from Apr to Dec 2007 in the second year when concentrations were greater than the control at both depths (Figs 17 and 18), TN was less than the control at 0 and 3 m depths for both years (Figs 19 and 20), Chl *a* was generally similar to the control at 0 and 3 m depths for Nov 2006 to Apr 2007 but much lower than the control from Apr to Nov for both years (Fig. 21,22), and concentrations SS were greater than the control at 0 and 3 m depths for both years (Figs 23 and 24).

3.4.3 Scenario III (Ngarotoiti diversion and permanent weir)

When scenarios 1 (divert D 13) and 2 (increase winter water level) were combined, DO remained similar to the control at 0 and 3 m depths for both years (Figs 15, 16), TP remained similar to the control at 0 and 3 m depths for Dec to July of the first year then was much less than the control for the remainder of the first year and for the second year (Figs 17, 18), TN was less than the control at 0 and 3 m depths, particularly from Aug to Mar for both years, (Figs 19, 20), Chl *a* was reduced slightly from the control at 0 and 3 m depths for Nov 2006 to Apr 2007 and was much less than the control for the period Apr to Nov of both years (Figs 21, 22), and concentrations of SS became increasingly greater than the control at 0 and 3 m depths over the two years (Figs 23, 24).

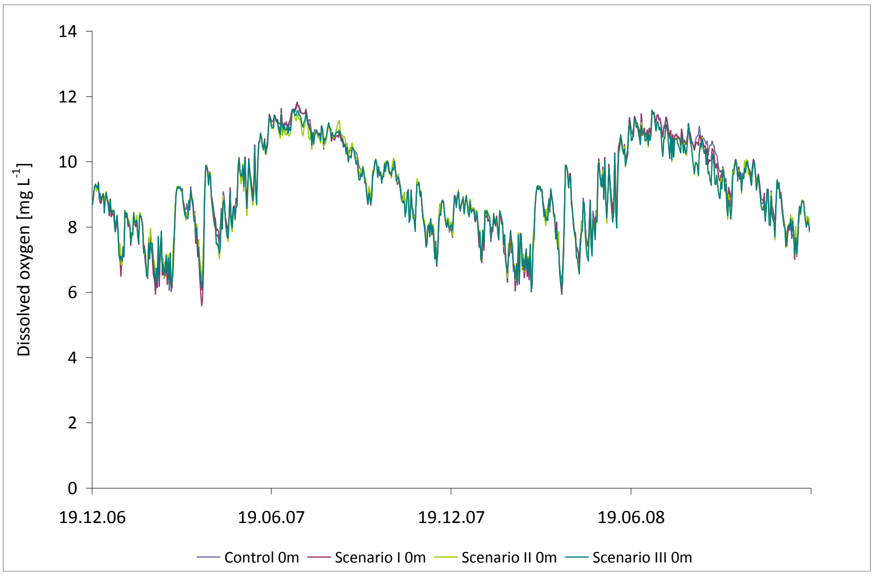

Figure 15: Dissolved oxygen concentrations [mg L^{-1}] for Control [0m], Scenario I [0m], Scenario II [0m], and Scenario III [0m] based on simulations with DYRESM-CAEDYM.

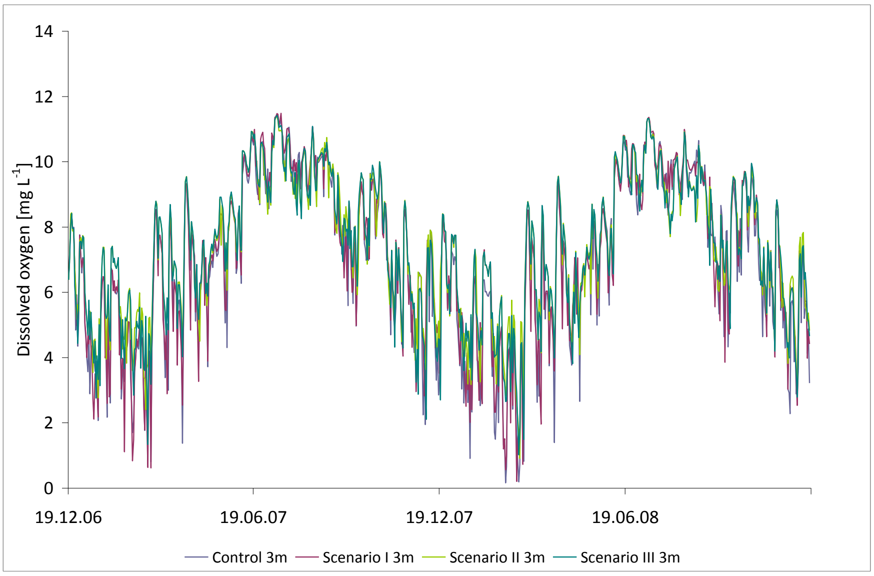

Figure 16: Dissolved oxygen concentrations [mg L^{-1}] for Control [3m], Scenario I [3m], Scenario II [3m], and Scenario III [3m] based on simulations with DYRESM-CAEDYM.

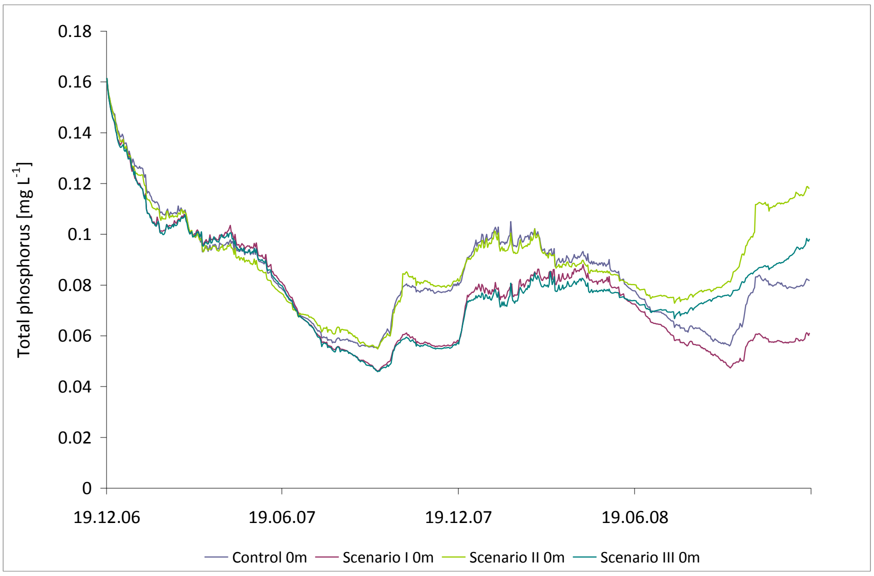

Figure 17: Total phosphorus concentrations [mg L^{-1}] for Control [0m], Scenario I [0m], Scenario II [0m], and Scenario III [0m] based on simulations with DYRESM-CAEDYM.

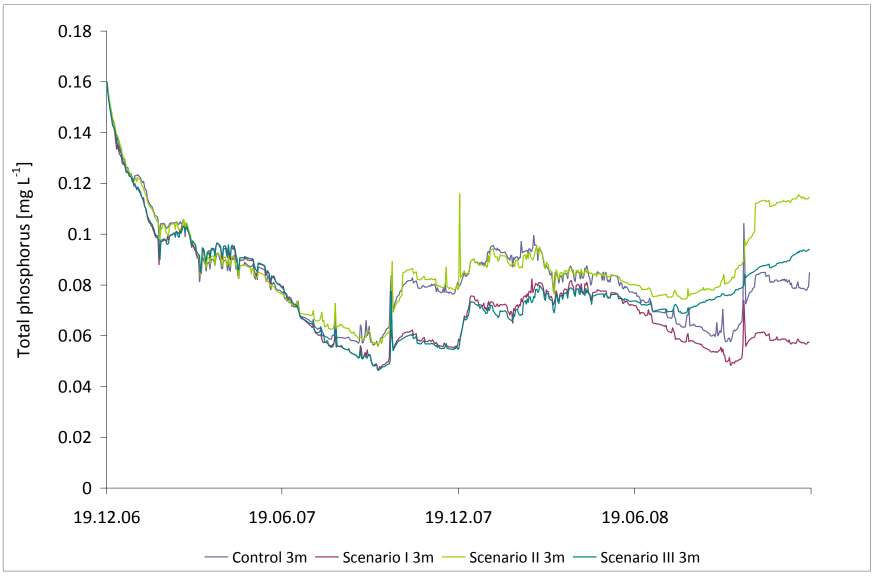

Figure 18: Total phosphorus concentrations [mg L^{-1}] for Control [3m], Scenario I [3m], Scenario II [3m], and Scenario III [3m] based on simulations with DYRESM-CAEDYM.

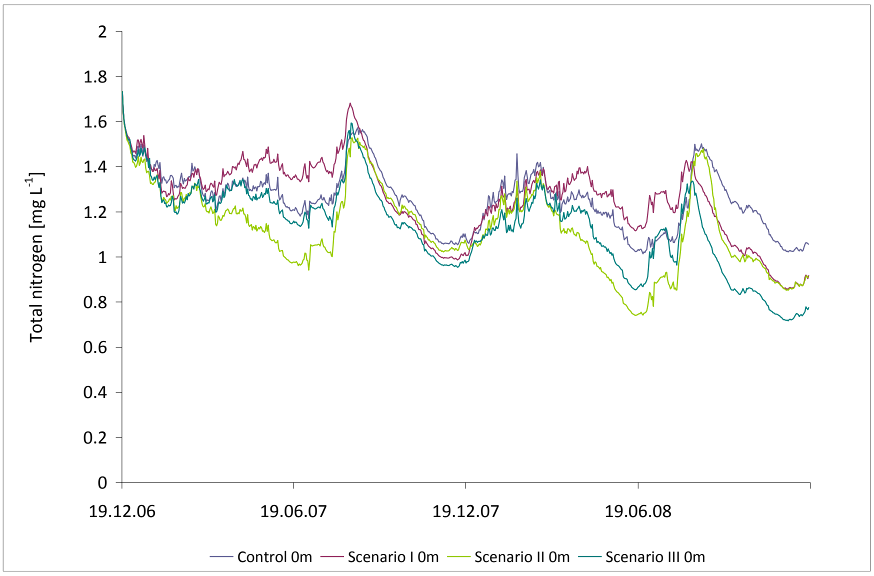

Figure 19: Total nitrogen concentrations [mg L^{-1}] for Control [0m], Scenario I [0m], Scenario II [0m], and Scenario III [0m] based on simulations with DYRESM-CAEDYM.

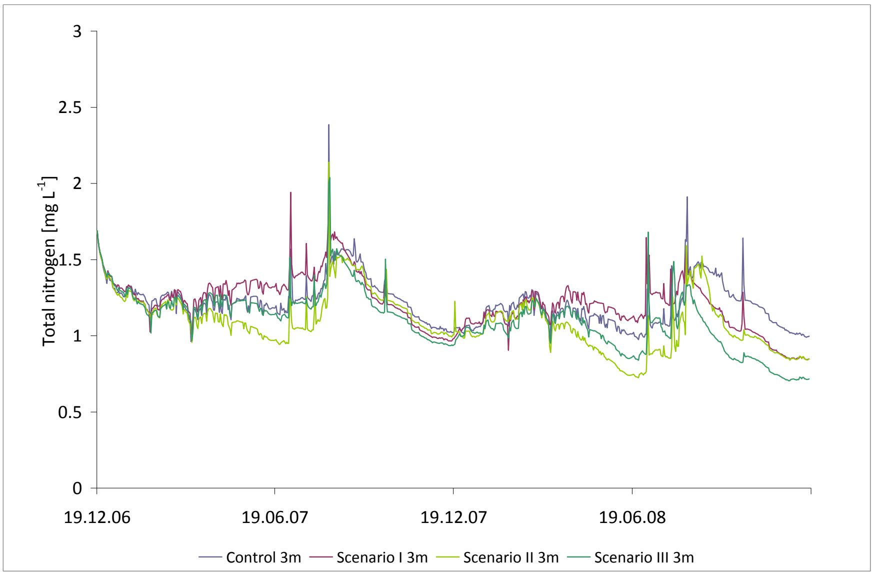

Figure 20: Total nitrogen concentrations [mg L^{-1}] for Control [3m], Scenario I [3m], Scenario II [3m], and Scenario III [3m] based on simulations with DYRESM-CAEDYM.

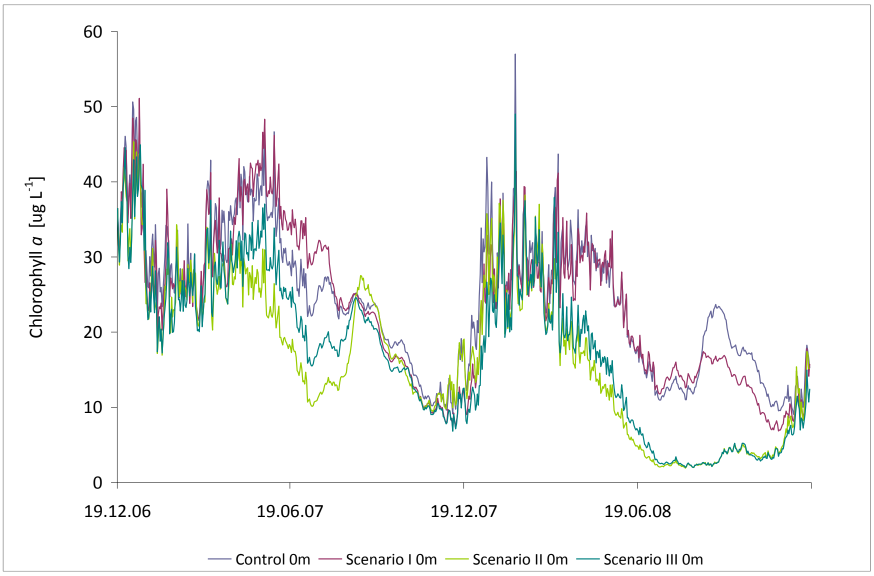

Figure 21: Chlorophyll *a* concentrations [ug L^{-1}] for Control [0m], Scenario I [0m], Scenario II [0m], and Scenario III [0m] based on simulations with DYRESM-CAEDYM.

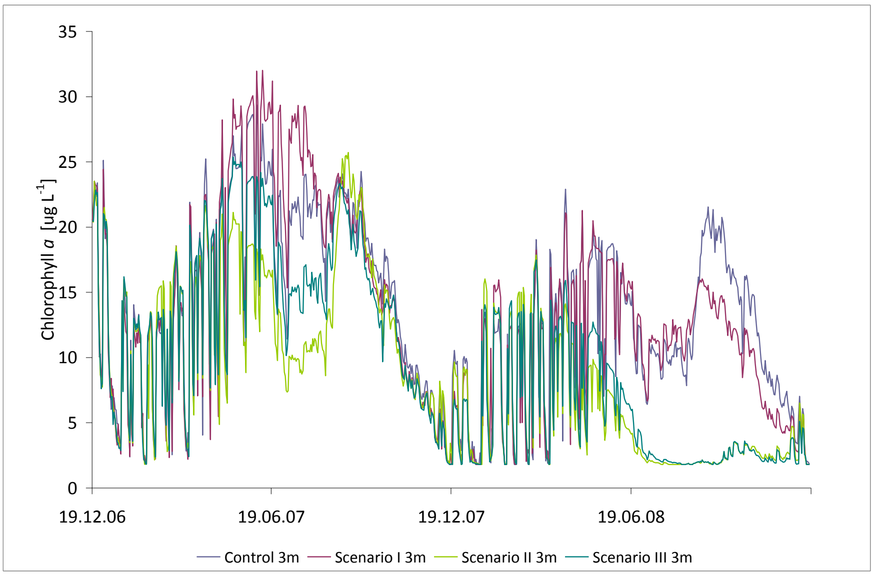

Figure 22: Chlorophyll *a* concentrations [ug L^{-1}] for Control [3m], Scenario I [3m], Scenario II [3m], and Scenario III [3m] based on simulations with DYRESM-CAEDYM.

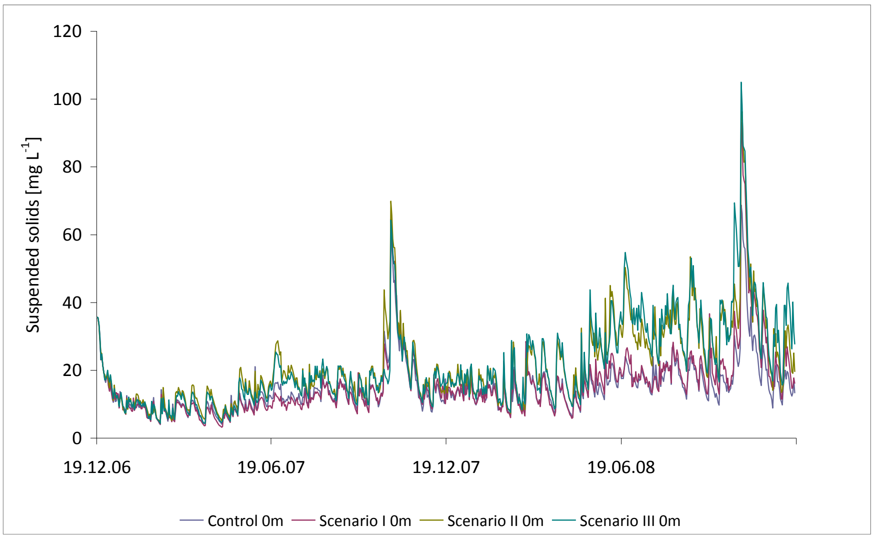

Figure 23: Suspended solid concentrations [mg L^{-1}] for Control [0m], Scenario I [0m], Scenario II [0m], and Scenario III [0m] based on simulations with DYRESM-CAEDYM.

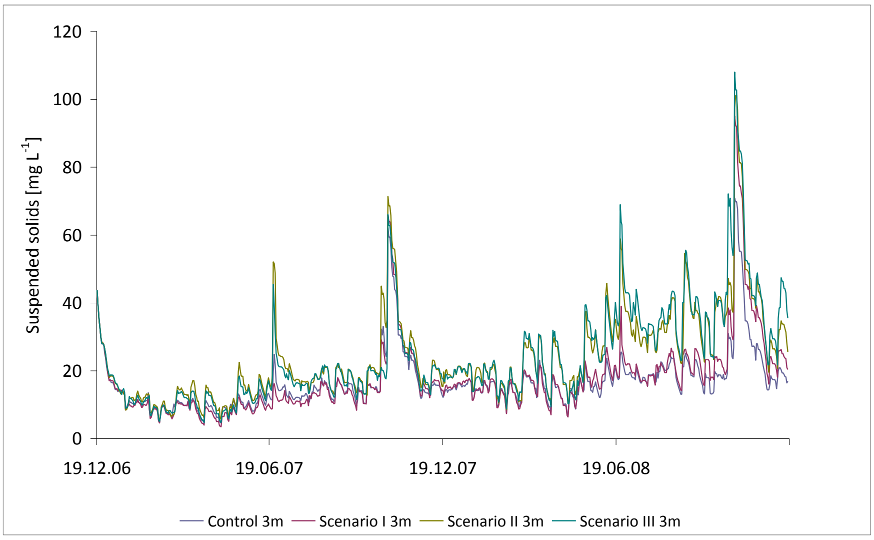

Figure 24: Suspended solid concentrations [mg L^{-1}] for Control [3m], Scenario I [3m], Scenario II [3m], and Scenario III [3m] based on simulations with DYRESM-CAEDYM.

3.4.4 Scenario IV (water level reduced by 0.4 m)

When the minimum water level was reduced by 0.4m in the simulations, DO remained similar to the control at 0 and 3 m depths for both years (Figs 25, 26), TP was much greater than the control at 0 and 3 m depths for both years (Figs 27, 28), TN was much greater than the control at 0 and 3 m depths for both years (Figs 29, 30); Chl *a* was much greater than the control at 0 and 3 m depths for both years (Figs 31, 32); SS were much lower than the control at 0 and 3 m depths for both years (Figs 33, 34), and water temperatures increased by up to 3 ^{o}C.

3.4.5 Scenario V-1 (sediment removal, low nutrient release)

When 20 cm of sediment from the entire bottom of the lake was removed and the release rates were changed from 0.02 to 0.008 g m^{-2} d^{-1} PO_4 and 0.05 to 0.14 g m^{-2} d^{-1} for NH_4, the model simulated indicated that DO was remain similar to the control at 0 and 3 m depths for both years at 0 and 3 m depths (Figs 25, 26), TP was less than the control especially from Mar to Sept at both depths for both years (Figs 27, 28), TN was less than the control especially from Jan to Aug for both years and both depths (Figs 29, 30), Chl *a* was a little greater than the control for Sep to Dec but much less than the control from Dec to Aug at 0 and 3 m depths for both years (Figs 31, 32) and SS were slightly greater than the control at 0 and 3 m depths for both years (Figs 33, 34).

3.4.6 Scenario V-2 (sediment removal, high nutrient release)

When 20 cm of sediment from the entire bottom of the lake is removed and the release rates are changed from 0.02 to 0.017 g m^{-2} d^{-1} PO_4 and 0.05 to 0.14 g m^{-2} d^{-1} for NH_4 then the concentrations for DO remained similar to the control at 0 and 3 m depths for both years (Figs 25, 26), and TP, TN and Chl *a* wee similar but slightly higher than those in scenario V-1 (Figs 27-32), while SS was slightly lower than for the scenario V-1 (Figs 33, 34)

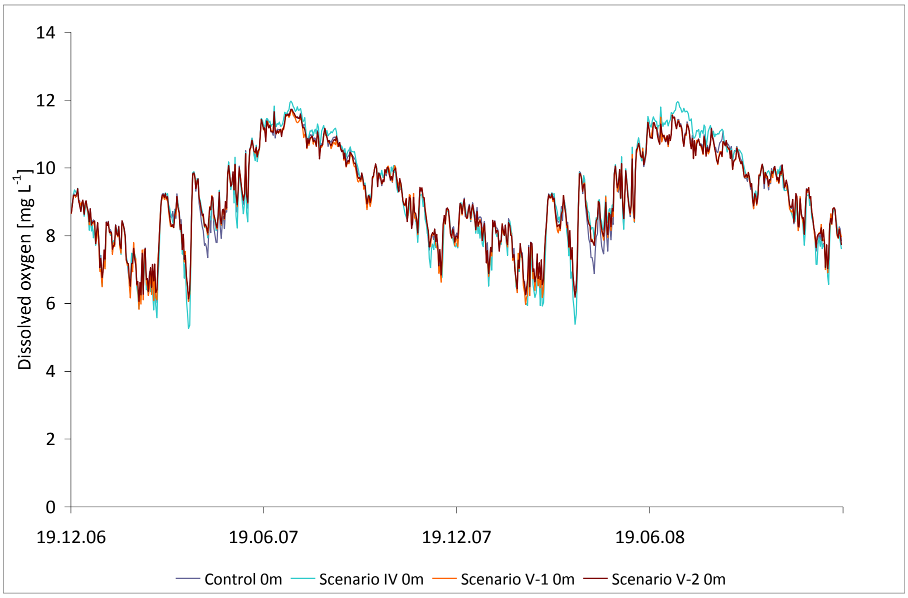

Figure 25: Dissolved oxygen concentrations [mg L^{-1}] for Control [0m], Scenario IV [0m], Scenario V-1 [0m], and Scenario V-2 [0m] based on simulations with DYRESM-CAEDYM.

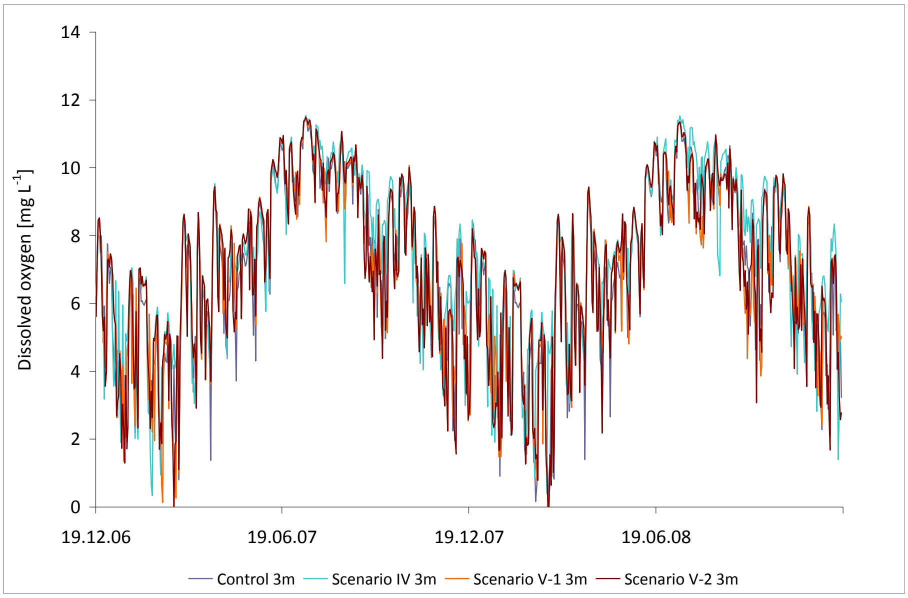

Figure 26: Dissolved oxygen concentrations [mg L^{-1}] for Control [3m], Scenario IV [2.54m], Scenario V-1 [3m], and Scenario V-2 [3m] based on simulations with DYRESM-CAEDYM.

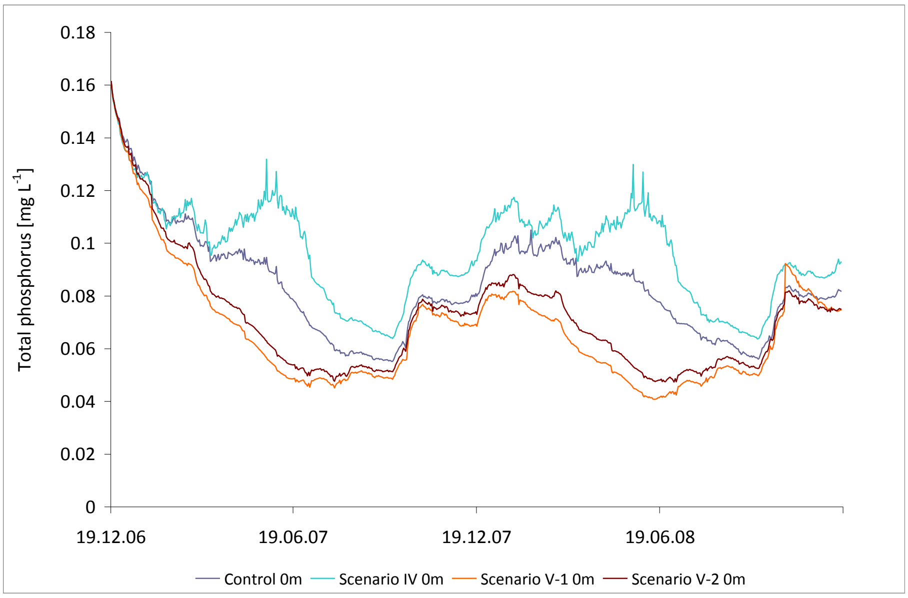

Figure 27: Total phosphorus concentrations [mg L^{-1}] for Control [0m], Scenario IV [0m], Scenario V-1 [0m], and Scenario V-2 [0m] based on simulations with DYRESM-CAEDYM.

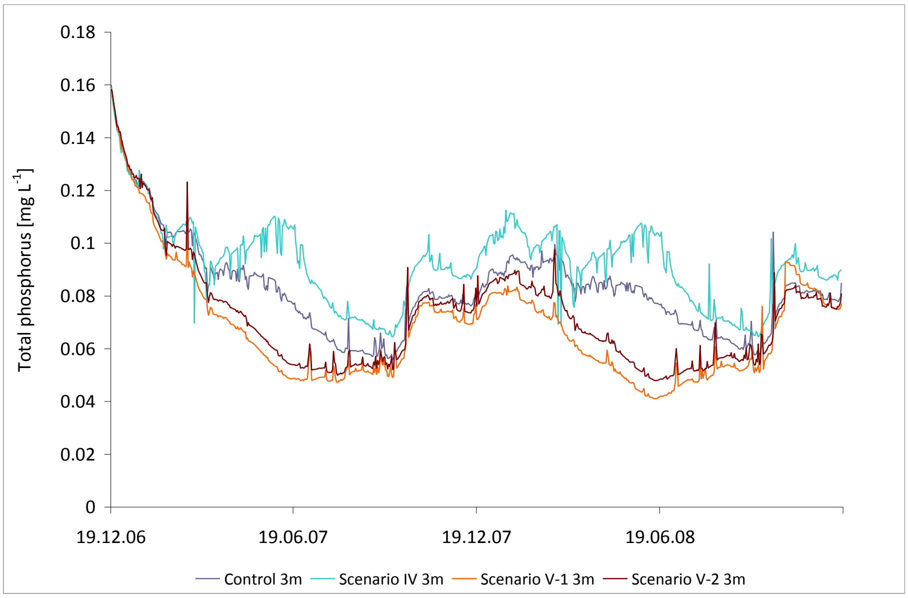

Figure 28: Total phosphorus concentrations [mg L^{-1}] for Control [3m], Scenario IV [2.54m], Scenario V-1 [3m], and Scenario V-2 [3m] based on simulations with DYRESM-CAEDYM.

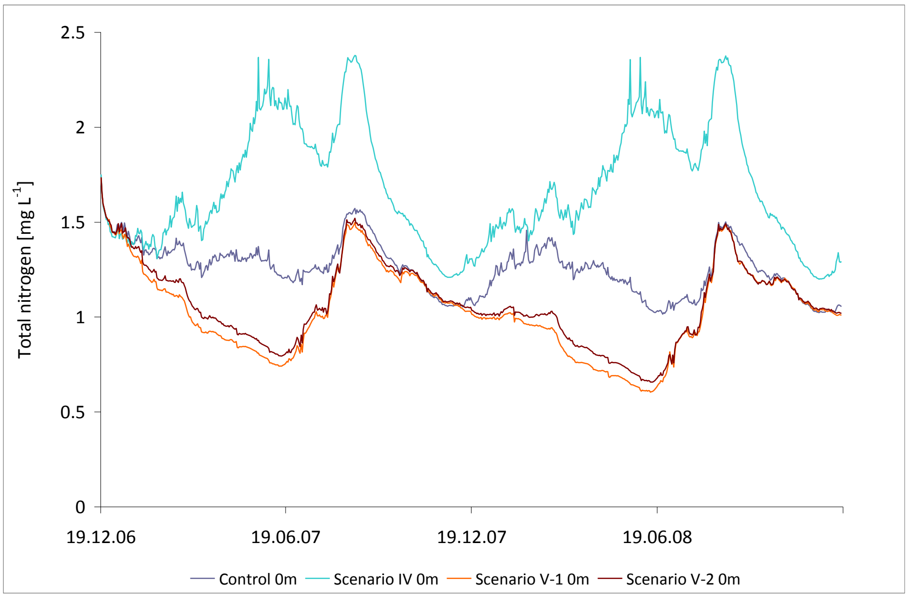

Figure 29: Total nitrogen concentrations [mg L^{-1}] for Control [0m], Scenario IV [0m], Scenario V-1 [0m], and Scenario V-2 [0m] based on simulations with DYRESM-CAEDYM.

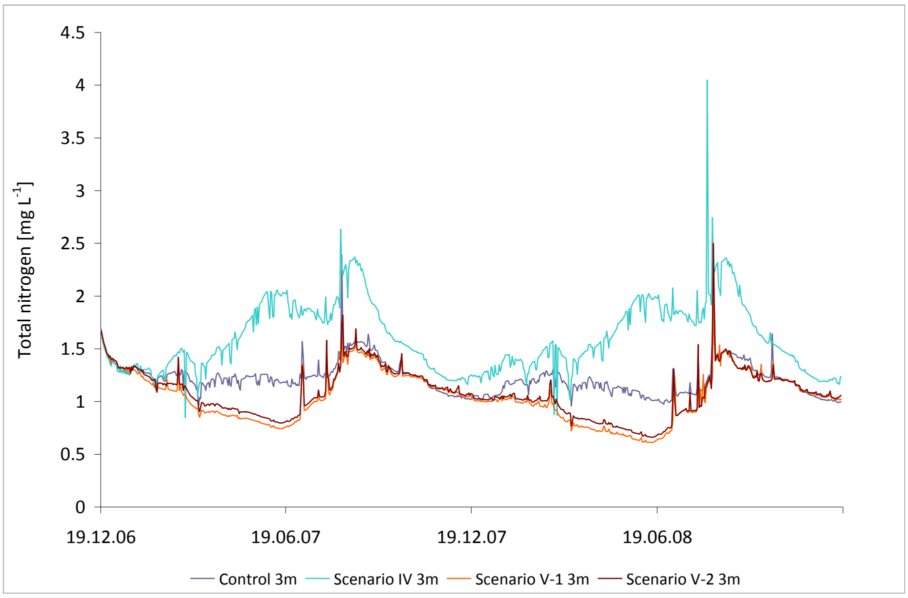

Figure 30: Total nitrogen concentrations [mg L^{-1}] for Control [3m], Scenario IV [2.54m], Scenario V-1 [3m], and Scenario V-2 [3m] based on simulations with DYRESM-CAEDYM.

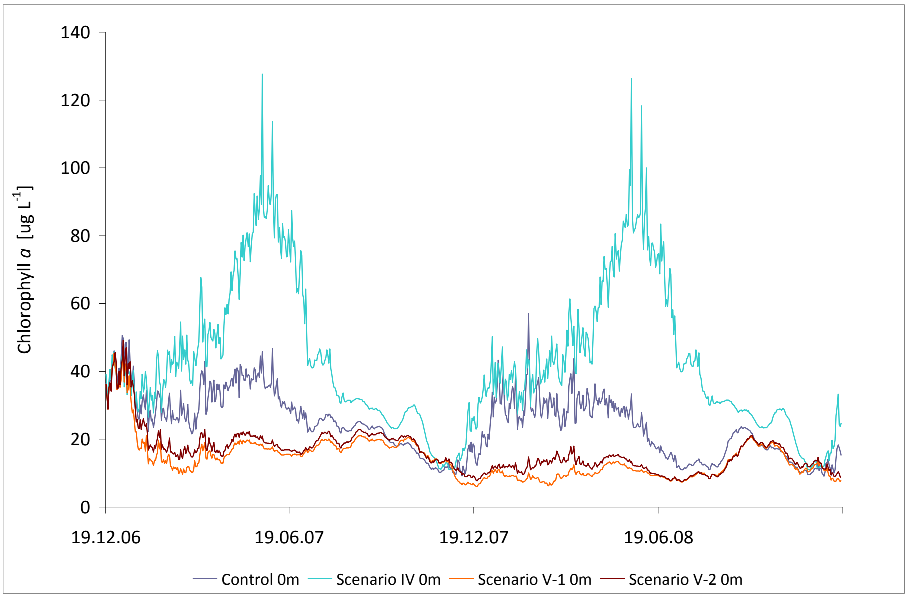

Figure 31: Chlorophyll *a* concentrations [ug L^{-1}] for Control [0m], Scenario IV [0m], Scenario V-1 [0m], and Scenario V-2 [0m] based on simulations with DYRESM-CAEDYM.

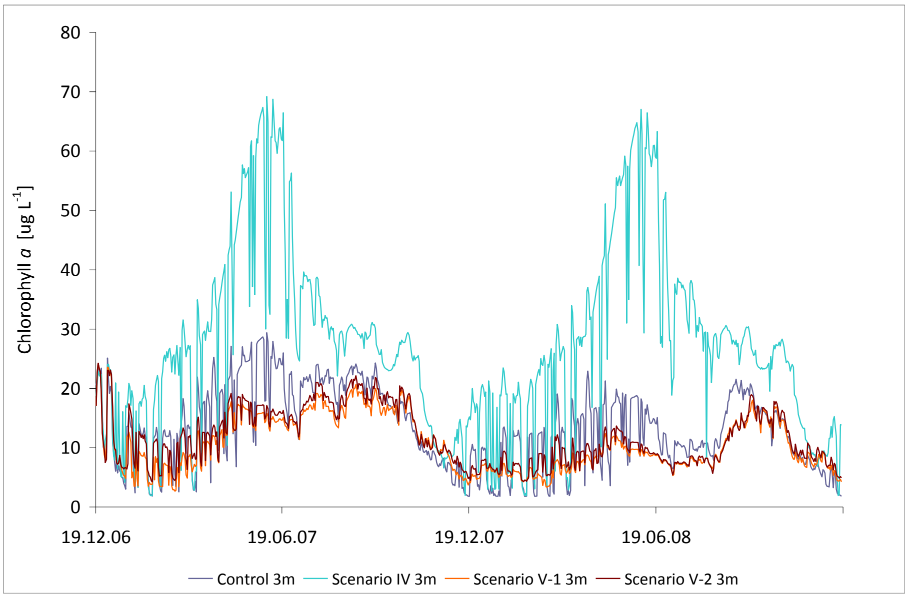

Figure 32: Chlorophyll *a* concentrations [ug L^{-1}] for Control [3m], Scenario IV [2.54m], Scenario V-1 [3m], and Scenario V-2 [3m] based on simulations with DYRESM-CAEDYM.

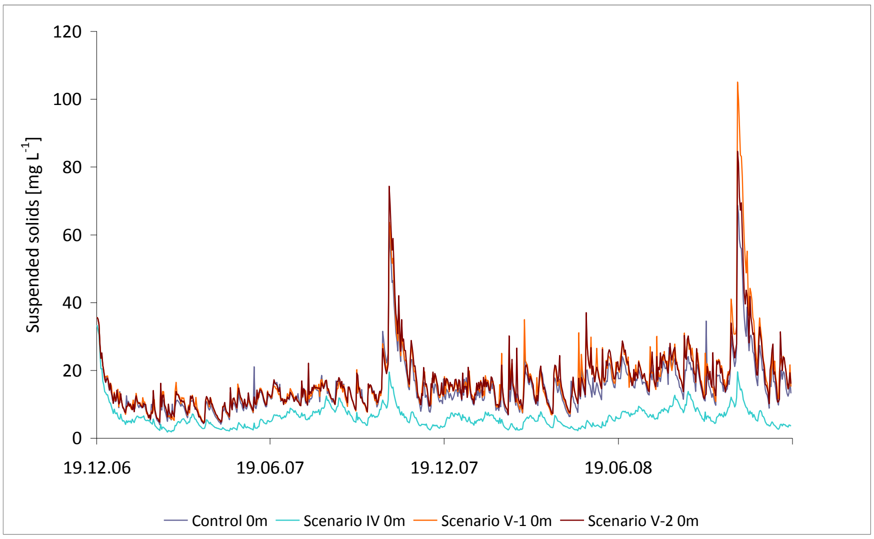

Figure 33: Suspended solid concentrations [mg L^{-1}] for Control [0m], Scenario IV [0m], Scenario V-1 [0m], and Scenario V-2 [0m] based on simulations with DYRESM-CAEDYM.

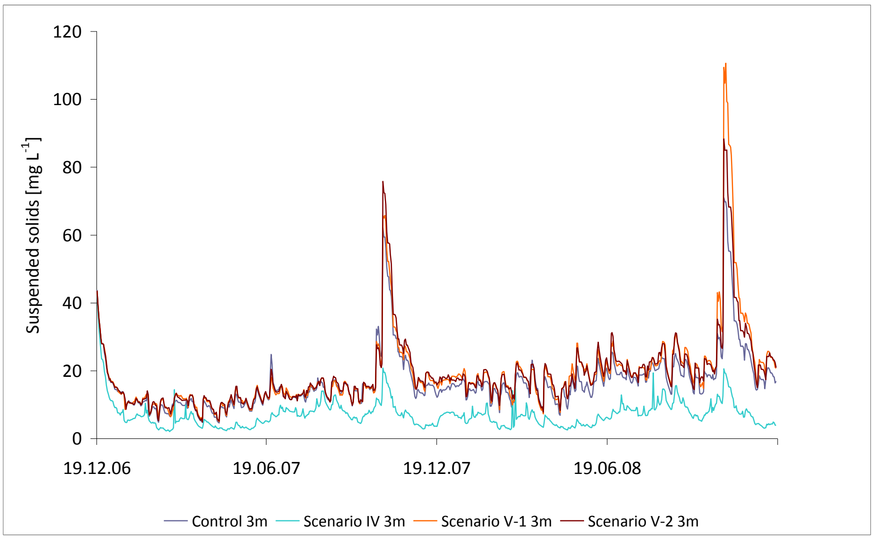

Figure 34: Suspended solid concentrations [mg L^{-1}] for Control [3m], Scenario IV [3m], Scenario V-1 [3m], and Scenario V-2 [3m] based on simulations with DYRESM-CAEDYM.

3.4.7 Scenario VI (catchment nutrient reductions)

When nutrient concentrations in the model inflow were reduced by 33% (Scenario VI 33%) and by 50% (Scenario VI 50%) then there was absolutely no or minimal difference to the DO, TP, TN, Chl *a* and SS concentrations for scenario VI at 0 and 3 m depths for both years (Fig. 35-44).

Comment [DH4]: revise pending simulation results.

3.4.8 Scenario VII (wave barriers)

This scenario involved reducing wind speed by 50% in order to simulate the effect of wave barriers that separated the lake into roughy 500 m maximum fetch lenghts. The simulations showed that DO concentrations were considerable less than those of the control at 0 and 3 m depths for both years (Figs 35 and 36); TP, TN and Chl *a* are generally much greater than the control except between for the period Sep and Dec for both years (Figs 37 and 42), SS concentrations are less than those in the control at 0 and 3 m depths for both years (Fig. 43,44) and that temperatures increased by up to 3.5^{o}C.

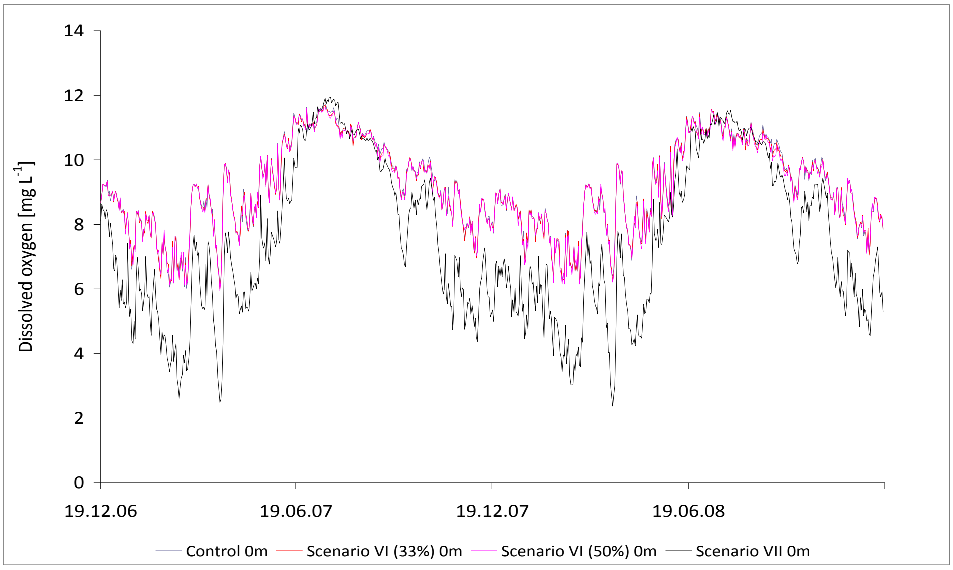

Figure 35: Dissolved oxygen concentrations [mg L^{-1}] for Control [0m], Scenario VI (33%) [0m], Scenario VI (50%) [0m], and Scenario VII [0m] based on simulations with DYRESM-CAEDYM.

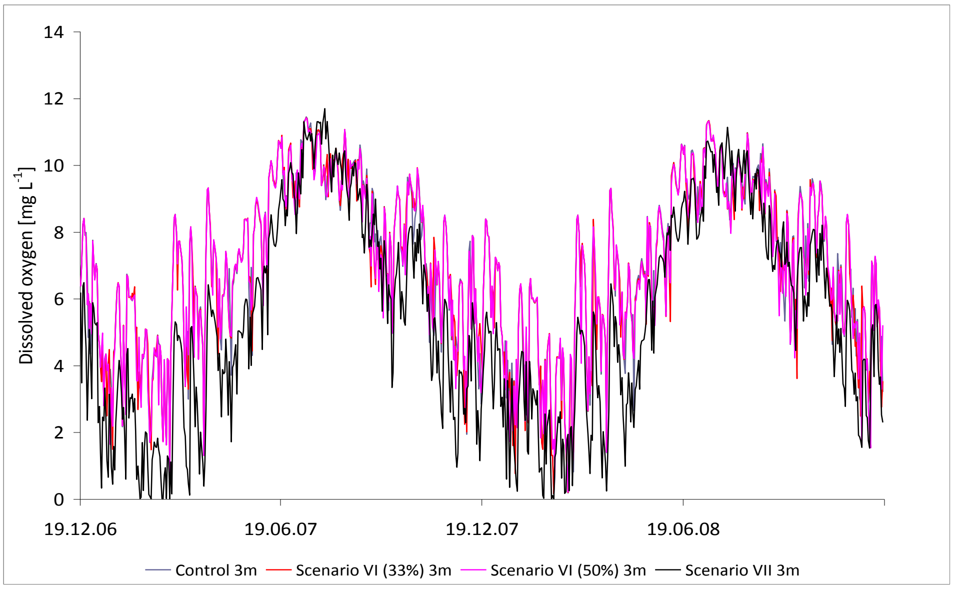

Figure 36: Dissolved oxygen concentrations [mg L^{-1}] for Control [3m], Scenario VI (33%) [3m], Scenario VI (50%) [3m], and Scenario VII [3m] based on simulations with DYRESM-CAEDYM.

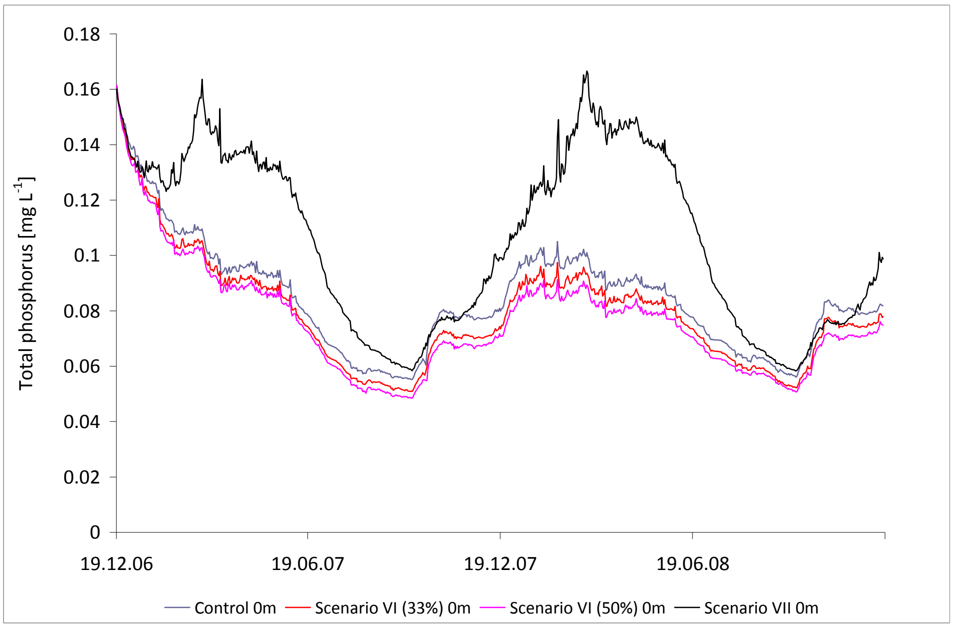

Figure 37: Total phosphorus concentrations [mg L^{-1}] for Control [0m], Scenario VI (33%) [0m], Scenario VI (50%) [0m], and Scenario VII [0m] based on simulations with DYRESM-CAEDYM.

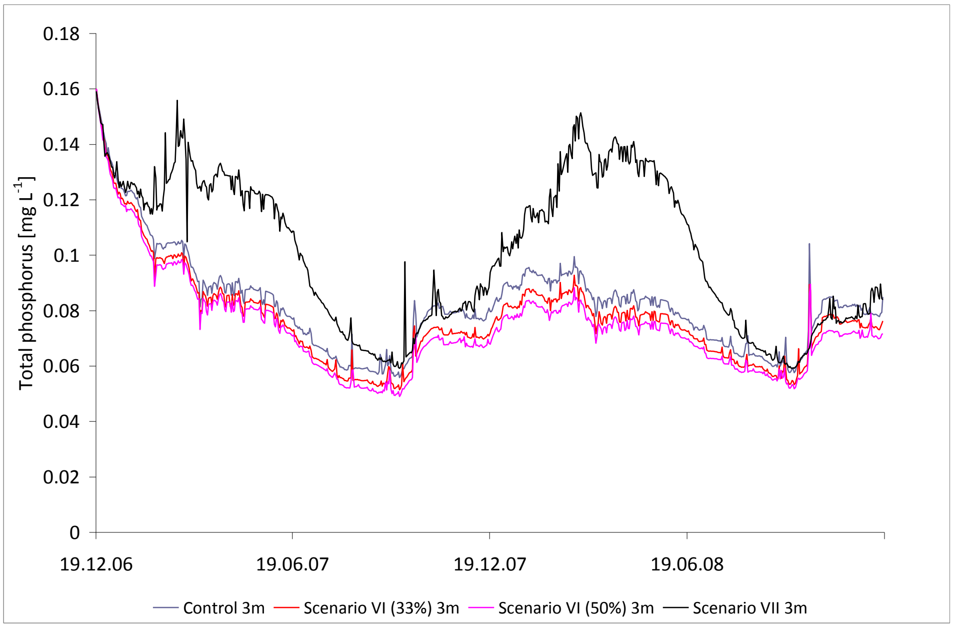

Figure 38: Total phosphorus concentrations [mg L^{-1}] for Control [3m], Scenario VI (33%) [3m], Scenario VI (50%) [3m], and Scenario VII [3m] based on simulations with DYRESM-CAEDYM.

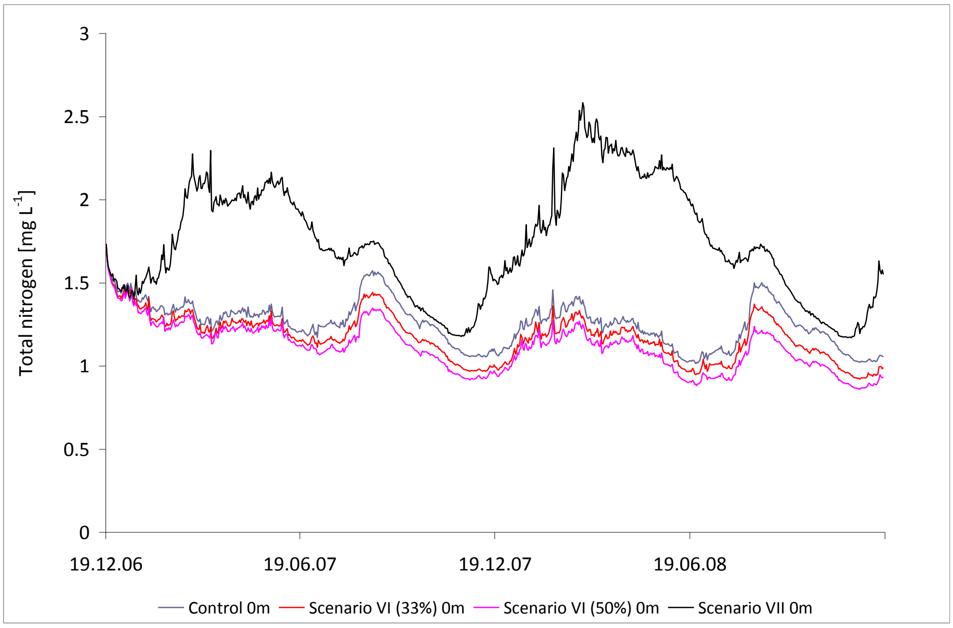

Figure 39: Total nitrogen concentrations [mg L^{-1}] for Control [0m], Scenario VI (33%) [0m], Scenario VI (50%) [0m], and Scenario VII [0m] based on simulations with DYRESM-CAEDYM.

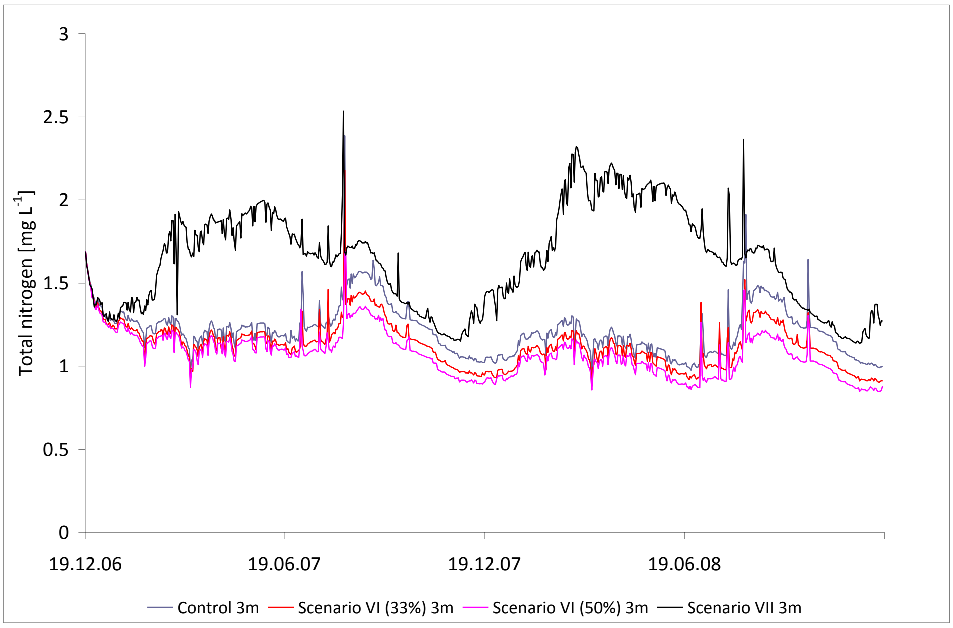

Figure 40: Total nitrogen concentrations [mg L^{-1}] for Control [3m], Scenario VI (33%) [3m], Scenario VI (50%) [3m], and Scenario VII [3m] based on simulations with DYRESM-CAEDYM.

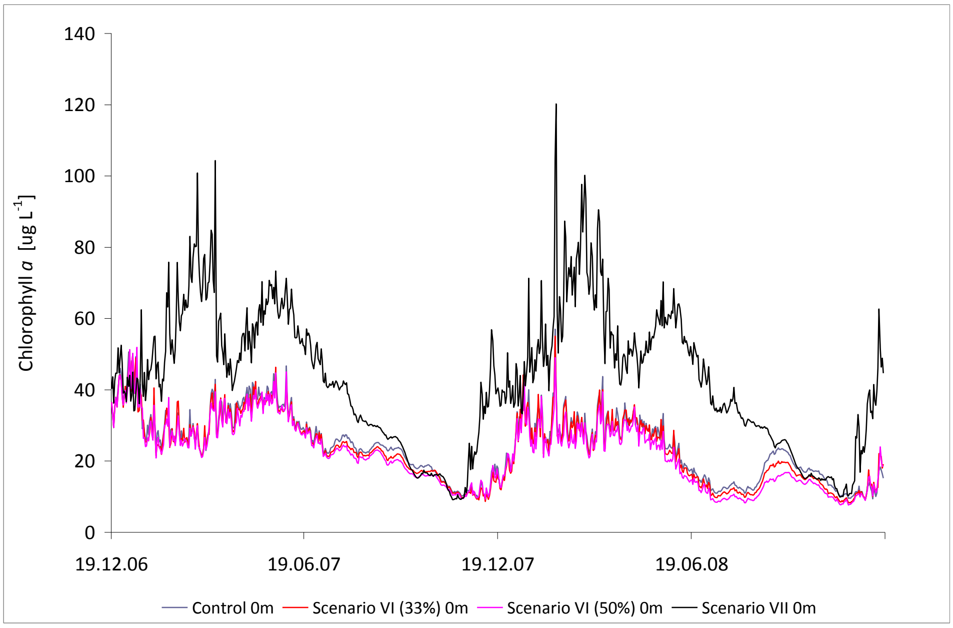

Figure 41: Chlorophyll *a* concentrations [ug L^{-1}] for Control [0m], Scenario VI (33%) [0m], Scenario VI (50%) [0m], and Scenario VII [0m] based on simulations with DYRESM-CAEDYM.

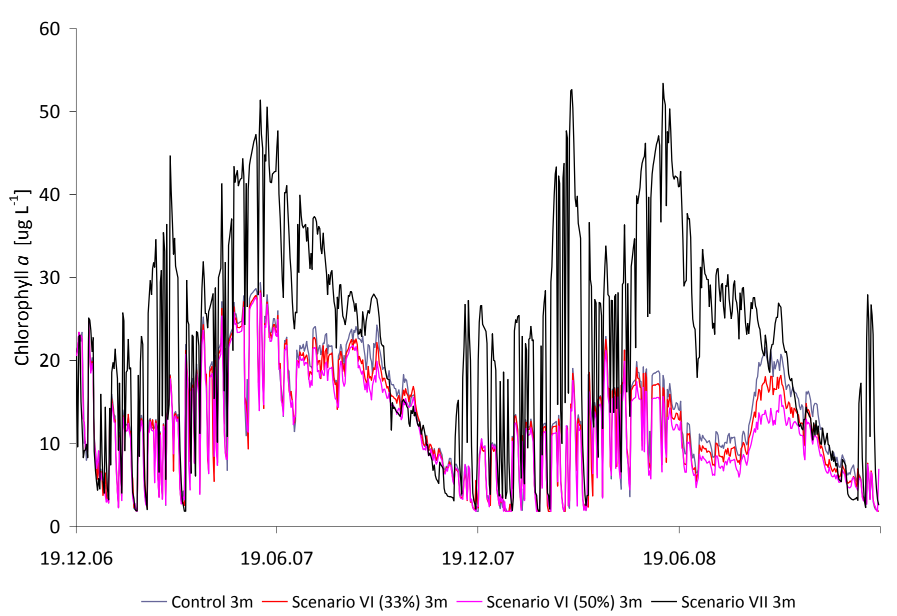

Figure 42: Chlorophyll *a* concentrations [ug L^{-1}] for Control [3m], Scenario VI (33%) [3m], Scenario VI (50%) [3m], and Scenario VII [3m] based on simulations with DYRESM-CAEDYM.

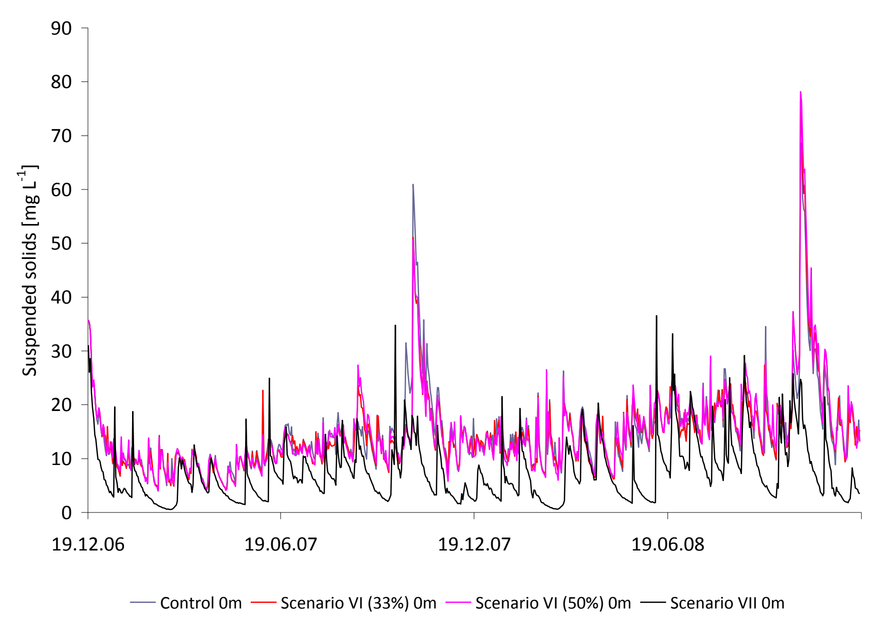

Figure 43: Suspended solids concentrations [mg L^{-1}] for Control [0m], Scenario VI (33%) [0m], Scenario VI (50%) [0m], and Scenario VII [0m] based on simulations with DYRESM-CAEDYM.

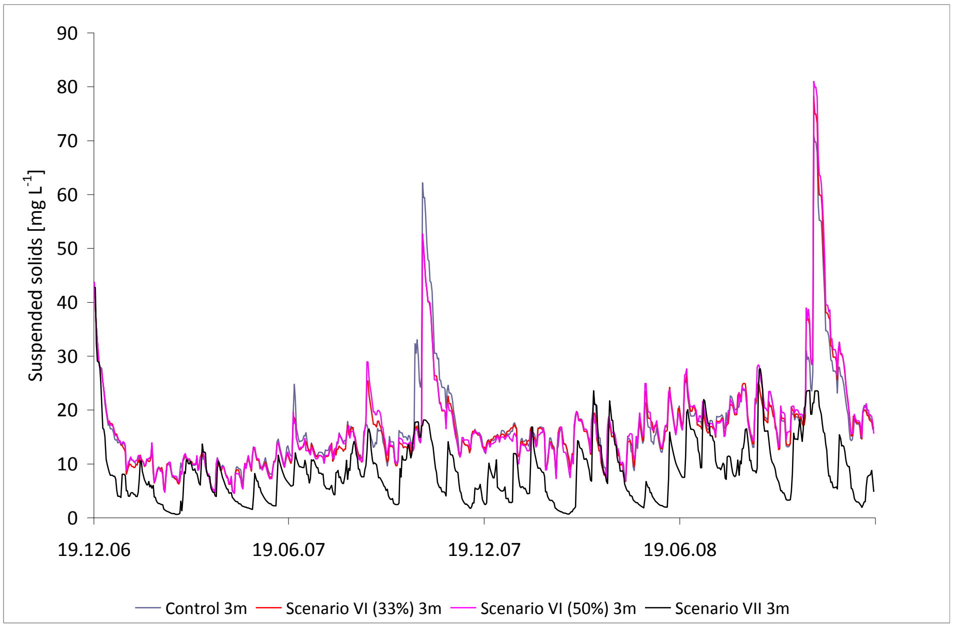

Figure 44: Suspended solids concentrations [mg L^{-1}] for Control [3m], Scenario VI (33%) [3m], Scenario VI (50%) [3m], and Scenario VII [3m] based on simulations with DYRESM-CAEDYM.

In summary, Scenario V showed the greatest proportional reductions in TP, TN and Chl *a* but some increase in SS, Scenario IV and VII showed the greatest reduction of SS but had increased TP, TN and Chl *a*, Scenarios II and III showed little effect on nutrients but showed reduced Chl *a* and increased SS concentrations whereas Scenarios I and VI had relatively little effect on all variables (Table 5).

Table 5: Percentage difference from Control, calculated from the sum of output data for 2 years.

Scenario I: Ngarotoiti diversion
Scenario II: permanent weir
Scenario III: Ngarotoiti diversion and permanent weir
Scenario IV: water level reduced by 0.4 m
Scenario V-1: sediment removal, with low nutrient release (V-1) and high nutrient release (V-2)
Scenario VI: catchment nutrient reductions, by 33% and 50%.
Scenario VII: wave barrier

	Sc I	**Sc II**	**Sc III**	**Sc IV**	**Sc V-1**	**Sc V-2**	**Sc VI (33%)**	**Sc VI (50%)**	**Sc VII**
DO at 0 m depth	-0.4	-0.7	-1.0	0.3	-0.2	0.2	-0.3	-0.5	-18.3
DO at 3 m depth	1.6	5.8	5.4	6.4	0.6	0.3	-0.2	-0.4	-21.6
TP at 0 m depth	-10.6	5.3	-5.7	14.5	-20.1	-15.1	-6.1	-9.6	25.5
TP at 3 m depth	-11.0	6.2	-5.4	12.2	-17.1	-11.8	-6.3	-9.9	22.8
TN at 0 m depth	0.2	-10.4	-9.6	34.2	-17.5	-14.6	-6.5	-11.2	38.3
TN at 3 m depth	0.2	-9.8	-8.9	31.8	-13.6	-10.8	-7.0	-11.6	35.2
Chl *a* at 0 m depth	-3.6	-31.0	-28.4	75.8	-40.9	-32.9	-4.5	-9.1	75.6
Chl *a* at 3 m depth	-0.8	-33.5	-27.8	105.5	-20.2	-12.2	-6.2	-12.0	70.2
SS at 0 m depth	5.3	42.4	44.9	-58.4	13.9	12.3	-1.4	0.5	-49.4
SS at 3 m depth	5.9	43.8	45.3	-57.3	14.9	13.4	-1.4	0.5	-48.3

4 Discussion

It is important in the long term to reduce external nutrient loading as well as internal loading when endeavouring to improve lake water quality (Søndergaard *et al*. 2003). Even when external loading is reduced significantly however, often high rates of internal loading limit any immediate improvement of lake water quality (Søndergaard *et al*. 2003; Jeppesen *et al*. 2005; Burger *et al*. 2008). Shallow lakes typically undergo intense mixing (Nixdorf & Denke, 1997) and resuspension of sediments due to benthic shear stress (Hamilton & Mitchell, 1997) and convective heat exchanges (Spigel & Imberger, 1987) that may penetrate the sediments and entrain sediment porewaters, ensuring a light climate that enhances nutrient supply to phytoplankton. Thus restorative measures are often ineffective if internal nutrient load is ignored (Nixdorf & Denke, 1997). Change in external loading may not have an immediate effect but to gain long term improvement in water quality it must be part of the restoration plan as it is this external load that eventually becomes the internal load (Søndergaard *et al*. 2003).

The model presented in this report is based on a culmination of various people's work and a very limited data set, thus the validity of its output data is uncertain. Calibrations were performed on data collected in the lake from December 2006 to May 2007, yet the model has been formulated for a year using averaging, calculation of missing values using known mathematical relationships (eg the water balance equation), and proportional and regressional relationships to fill the large gaps in actual data. Also, the second year of the model used looped data. Thus care must be taken when interpreting the results of the various restoration scenarios and seasonal dynamics of the lake would become more apparent in the following years of simulation with a more complete data set. Instead we have proven that the lake did not show a state of equilibrium and therefore the simulations would have to be long-term before reaching a new equilibrium for water quality after nutrient reduction.

Despite this, the results of the restoration scenarios are as might be expected with the exception of increases in suspended sediments with deepening the lake (Scenario II and III) and removal of 20 cm sediment (Scenario V). We consider this to be due to the difficulty of capturing actual resuspension events with the model as the SS, once suspended, needs more time to settle out before the next resuspension event occurs.

Reduction of nutrients by 33% and 50% (Scenario VI) had a limited effect on the water quality. This may be due to the fact that effect of change of land use, that is reduced external loading, can be delayed by internal loading for about 10-15 years (Jeppesen *et al*. 2005).

Although lowering the lake by 0.4 m (Scenario IV) and reducing wind with wind breaks (Scenario VII) had the most beneficial effect in reducing suspended sediments, both actions increased nutrients and Chl *a* which is likely a result of increased water temperatures. Thus, it is not recommended that either of these options be considered for restoration management.

Scenario I, diverting the major inflow (D13; 39% of the total inflow) into the outflow (D14) did not produce any strong differences but there was a decrease in the Chl *a* and TP concentrations in the second year. The limited effect is likely due to the slower, more long term effect of external loading on lake water quality as referred to earlier. By leaving the weir in all year as well as diverting D13 (Scenario III), there was a greater reduction of nutrients but the large increase in SS is an unexpected result. These options may be considered as part of an integrated management plan which addresses both external and internal loading. It is advised that a long term monitoring plan takes place to better establish the water balance and further modelling is done on a larger data set to resolve the SS concentrations better before taking action.

Modelled results suggest that removal of 20 cm of surficial sediment in Scenario V would produce the greatest immediate benefit to the lake water quality with reduction of TP, TN and Chl *a* concentrations but an unexpected increase in suspended solids. The nutrient and Chl *a* reductions are consistent with Lake Ngaroto having a high internal loading that has a strong and immediate effect on the lake's water quality. Sediment removal as a management option is an expensive restoration option and inherent with it is the problem of where and how to dispose of the waste (Faithfull *et al*. 2005). The need to investigate restoration options thoroughly is highlighted by the finding of Faithfull *et al*. (2005) that, "..sediments below 20 cm still contain between 30 – 40 times more phosphate than found in the water column, and this phosphate would become available on exposure following dredging". As nutrient release from the sediment is the causal factor for poor water quality, an alternative option which may be considered is the application of modified zeolite flocculent, now that the efficacy of the material for P-removal has been established (Özkundakci & Hamilton, 2007). High sedimentation rates are an issue in Lake Ngaroto and would lead to repetition of either sediment removal or zeolite application being required every three to four years if external loading is not addressed (Faithfull *et al*. 2005)

This report does not include any restoration scenarios that simulate the effects of biomanipulation (e.g., pest fish removal) but this option should also be explored and considered for inclusion into an integrated management plan.

It cannot be emphasised enough that a comprehensive and consistent monitoring plan should be in place to establish a baseline before changes are made. This would ensure that any effects resulting from management actions are measureable, and produce a strong basis for further research and more accurate and valid model results.

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Appendices

Appendix 1. Flow and in-lake water quality results for 7 March to 29 May, 2007 collected by Marcel Brokbartold and Christoph Brakel.

Table 1: Values for flow [m^3 d^{-1}], total nitrogen (TN) [mg L^{-1}], total phosphorous (TP) [mg L^{-1}], chlorophyll *a* (Chl *a*) [µg L^{-1}] and suspended solids (SS) [mg L^{-1}] for the inflows and outflow of Lake Ngaroto. See Figure 1 and Table 2 for the locations of the inflows and the outflow.

Site	**Date**	**Flow** [m3 d^{-1}]	**TN** [mg L^{-1}]	**TP** [mg L^{-1}]	**Chl *a*** [µg L^{-1}]	**SS** *inorganic* [mg L-1]
D1	14 May 07	0.0	1.26	0.06	2.0	< 2
D1	29 May 07	0.0	1.23	0.06	3.3	15
D5	07 March 07	0.0	0.45	0.06	No value	43
D5	23 March 07	0.0	0.83	0.14	1.2	15
D5	04 April 07	0.0	0.94	0.10	4.4	35
D5	16 April 07	0.0	0.95	0.13	4.2	< 2
D5	02 May 07	0.0	2.56	0.13	2.9	3
D5	14 May 07	0.0	1.07	0.08	2.8	2
D5	29 May 07	0.0	1.16	0.11	4.5	< 2
D13	07 March 07	0.0	1.42	0.03	4.7	13
D13	23 March 07	1244.2	1.65	0.09	8.8	32
D13	04 April 07	1658.9	1.54	0.18	10.8	6
D13	16 April 07	1658.9	1.63	0.13	3.6	< 2
D13	02 May 07	51258.9	2.89	0.27	113.8	6
D13	14 May 07	3317.8	1.34	0.09	5.9	< 2
D13	29 May 07	1850.7	1.62	0.14	7.2	< 2
D14 (outflow)	07 March 07	363.1	0.69	0.06	11.6	50
D14	23 March 07	6350.4	1.86	0.13	19.2	10
D14	04 April 07	6068.2	0.95	0.10	24.2	19
D14	16 April 07	6068.2	0.91	0.09	3.6	< 2
D14	02 May 07	189511.2	1.11	0.19	42.8	< 2
D14	14 May 07	7338.2	0.74	0.12	41.0	15
D14	29 May 07	9779.6	0.74	0.10	41.5	5
D16	07 March 07	0.0	0.53	0.06	1.3	33
D16	23 March 07	0.0	0.41	0.02	1.0	5
D16	04 April 07	0.0	0.48	0.02	1.1	13
D16	16 April 07	0.0	0.45	0.02	0.9	3
D16	02 May 07	0.0	2.74	0.03	2.1	< 2
D16	14 May 07	0.0	1.42	0.02	0.2	< 2
D16	29 May 07	0.0	1.47	0.05	0.8	< 2
D17	07 March 07	0.0	0.53	0.06	2.8	13
D17	23 March 07	0.0	1.01	0.07	1.7	2.5
D17	04 April 07	0.0	1.28	0.07	1.1	6
D17	16 April 07	0.0	1.01	0.06	3.5	< 2
D17	02 May 07	0.0	3.53	0.02	4.3	< 2
D17	14 May 07	0.0	0.98	0.04	3.6	5
D17	29 May 07	0.0	0.89	0.02	1.5	< 2
D20	07 March 07	0.0	No value *	No value *	No value *	No value *
D20	23 March 07	0.0	0.48	0.03	4.3	2.5

D20	04 April 07	0.0	0.32	0.03	3.7	5
D20	16 April 07	0.0	0.47	0.03	2.2	< 2
D20	02 May 07	0.0	2.22	0.02	4.2	< 2
D20	14 May 07	0.0	0.90	0.02	0.6	< 2
D20	29 May 07	0.0	0.97	0.01	5.2	20
D21	07 March 07	0.0	0.55	0.06	3.3	33
D21	23 March 07	0.0	0.41	0.04	0.7	< 2
D21	04 April 07	0.0	0.35	0.04	0.8	2
D21	16 April 07	0.0	0.69	0.05	1.5	< 2
D21	02 May 07	0.0	3.75	0.08	0.3	< 2
D21	14 May 07	0.0	1.20	0.05	0.7	2
D21	29 May 07	0.0	1.36	0.04	0.8	< 2
D22	07 March 07	0.0	1.99	0.20	44.0	155
D22	23 March 07	0.0	1.95	0.25	43.8	22.5
D22	04 April 07	0.0	1.27	0.19	43.1	8
D22	16 April 07	0.0	1.69	0.30	43.0	9
D22	02 May 07	0.0	1.96	0.04	34.3	< 2
D22	14 May 07	0.0	0.99	0.09	32.6	2
D22	29 May 07	0.0	0.88	0.03	35.3	< 2

* Water sample tube leaked.

Table 2: Concentrations of NH_4-N [mg L^{-1}], NO_3-N [mg L^{-1}] and PO_4-P [mg L^{-1}] for the inflows and the outflow of Lake Ngaroto. See Figure 1 and Table 2 for the locations of the inflows and the outflow.

Site	**Date**	**NH4** [mg L-1]	**NO3** [mg L-1]	**PO4** [mg L-1]
D1	14 May 07	0.056	0.409	0.012
D1	29 May 07	0.032	0.392	0.015
D5	07 March 07	0.129	0.116	0.020
D5	23 March 07	0.051	0.218	0.029
D5	04 April 07	0.065	0.215	0.009
D5	16 April 07	0.080	0.211	0.025
D5	02 May 07	0.163	1.674	0.024
D5	14 May 07	0.079	0.259	0.010
D5	29 May 07	0.104	0.331	0.006
D13	07 March 07	0.268	1.148	0.016
D13	23 March 07	0.299	0.630	0.050
D13	04 April 07	0.267	0.527	0.051
D13	16 April 07	0.038	0.889	0.054
D13	02 May 07	0.311	1.281	0.069
D13	14 May 07	0.343	0.460	0.064
D13	29 May 07	0.277	0.682	0.033
D14 (outflow)	07 March 07	0.035	0.332	0.009
D14	23 March 07	0.015	0.000	0.014
D14	04 April 07	0.020	0.013	0.000
D14	16 April 07	0.015	0.009	0.012
D14	02 May 07	0.012	0.004	0.006
D14	14 May 07	0.023	0.001	0.008
D14	29 May 07	0.006	0.001	0.006
D16	07 March 07	0.026	0.080	0.034
D16	23 March 07	0.021	0.061	0.018
D16	04 April 07	0.029	0.069	0.004
D16	16 April 07	0.028	0.135	0.013
D16	02 May 07	0.082	1.613	0.010
D16	14 May 07	0.000	0.544	0.007
D16	29 May 07	0.004	0.582	0.007
D17	07 March 07	0.036	0.056	0.012
D17	23 March 07	0.844	0.043	0.016
D17	04 April 07	0.268	0.162	0.025
D17	16 April 07	0.084	0.033	0.021
D17	02 May 07	0.066	1.743	0.004
D17	14 May 07	0.050	0.193	0.009
D17	29 May 07	0.088	0.117	0.009
D20	07 March 07	No value *	No value *	No value *
D20	23 March 07	0.042	0.009	0.019
D20	04 April 07	0.045	0.022	0.005
D20	16 April 07	0.044	0.036	0.014
D20	02 May 07	0.087	1.337	0.005
D20	14 May 07	0.002	0.127	0.004
D20	29 May 07	0.028	0.182	0.006
D21	07 March 07	0.043	0.005	0.012
D21	23 March 07	0.023	0.180	0.042
D21	04 April 07	0.028	0.211	0.029
D21	16 April 07	0.027	0.309	0.031
D21	02 May 07	0.145	1.762	0.051

D21	14 May 07	0.024	0.368	0.010
D21	29 May 07	0.069	0.493	0.012
D22	07 March 07	0.017	0.009	0.012
D22	23 March 07	0.017	0.011	0.016
D22	04 April 07	0.023	0.021	0.009
D22	16 April 07	0.017	0.003	0.013
D22	02 May 07	0.094	1.203	0.011
D22	14 May 07	0.060	0.198	0.007
D22	29 May 07	0.066	0.111	0.007

* Water sample tube leaked.

Table 3: Temperature [°C], concentrations of dissolved oxygen (DO) [mg L^{-1}], pH and conductivity [µS cm^{-1}] for the inflows and the outflow of Lake Ngaroto. See Figure. 1 and Table 2 for the locations of the inflows and the outflow.

Site	**Date**	**Temperature** [°C]	**DO** [mg L^{-1}]	**pH**	**Conductivity** [µS cm^{-1}]
D1	14 May 07	13.67	5.90	6.55	149
D1	29 May 07	11.12	8.60	6.77	133
D5	07 March 07	19.11	4.63	7.06	105
D5	23 March 07	17.15	5.57	6.85	135
D5	04 April 07	16.54	9.06	6.92	142
D5	16 April 07	14.22	7.99	6.76	135
D5	02 May 07	17.22	6.80	6.27	196
D5	14 May 07	14.47	7.23	6.42	149
D5	29 May 07	8.56	8.89	6.35	123
D13	07 March 07	17.80	4.00	6.72	218
D13	23 March 07	19.30	2.45	6.80	201
D13	04 April 07	18.37	3.30	6.97	188
D13	16 April 07	15.05	3.37	6.82	172
D13	02 May 07	17.17	3.16	6.64	187
D13	14 May 07	14.41	2.26	6.67	192
D13	29 May 07	10.58	5.85	6.85	156
D14 (outflow)	07 March 07	18.97	6.56	6.41	216
D14	23 March 07	22.90	9.34	7.75	164
D14	04 April 07	20.49	8.56	7.40	155
D14	16 April 07	16.20	8.84	7.20	143
D14	02 May 07	16.45	8.43	7.26	143
D14	14 May 07	15.64	11.08	7.70	144
D14	29 May 07	12.15	11.17	7.65	130
D16	07 March 07	18.44	7.81	7.19	123
D16	23 March 07	17.20	6.80	7.07	151
D16	04 April 07	16.30	5.57	7.03	150
D16	16 April 07	13.99	6.64	7.14	131
D16	02 May 07	16.44	6.49	6.23	228
D16	14 May 07	12.92	6.79	6.69	174
D16	29 May 07	7.80	8.43	6.86	125
D17	07 March 07	19.47	3.52	6.91	142
D17	23 March 07	too shallow	too shallow	too shallow	too shallow
D17	04 April 07	too shallow	too shallow	too shallow	too shallow
D17	16 April 07	too shallow	too shallow	too shallow	too shallow
D17	02 May 07	16.62	7.82	5.91	290
D17	14 May 07	12.46	6.49	6.22	150
D17	29 May 07	8.01	6.29	6.36	132
D20	07 March 07	too shallow	too shallow	too shallow	too shallow
D20	23 March 07	too shallow	too shallow	too shallow	too shallow
D20	04 April 07	too shallow	too shallow	too shallow	too shallow
D20	16 April 07	too shallow	too shallow	too shallow	too shallow
D20	02 May 07	16.37	6.59	6.87	182
D20	14 May 07	12.99	7.70	6.64	127
D20	29 May 07	6.79	10.03	6.66	108
D21	07 March 07	18.35	3.27	6.77	148
D21	23 March 07	17.85	9.22	7.06	103
D21	04 April 07	16.80	9.55	7.38	109
D21	16 April 07	14.31	10.14	7.26	95

D21	02 May 07	17.15	7.86	6.38	190
D21	14 May 07	14.57	11.26	7.09	109
D21	29 May 07	9.77	12.94	7.05	97
D22	07 March 07	21.53	5.63	6.98	158
D22	23 March 07	18.30	8.37	7.00	147
D22	04 April 07	17.09	7.50	7.10	144
D22	16 April 07	14.60	12.68	7.87	134
D22	02 May 07	16.93	7.00	6.34	168
D22	14 May 07	12.64	7.73	6.67	135
D22	29 May 07	8.04	8.74	6.75	116

Table 4: Values for flow [m^3 d^{-1}], total nitrogen (TN) [mg L^{-1}], total phosphorous (TP) [mg L^{-1}], chlorophyll *a* (Chl *a*) [µg L^{-1}] and suspended solids (SS) [mg L^{-1}] at the three stations (north, middle and south), and the three depths in the middle station, at the surface and 1.5 and 3.0 m. See Figure 1 and Table 2 for the locations of the three stations.

Site	**Date**	**TN** [mg L-1]	**TP** [mg L-1]	**Chl *a*** [µg L-1]	**SS** *inorganic* [mg L-1]
Middle 0.0m	07 March 07	1.380	0.141	12.39	50.50
Middle 0.0m	23 March 07	1.124	0.139	17.82	17.50
Middle 0.0m	04 April 07	0.930	0.127	28.97	35.00
Middle 0.0m	16 April 07	1.154	0.149	22.78	7.50
Middle 0.0m	02 May 07	1.037	0.115	25.61	31.25
Middle 0.0m	14 May 07	no value *	0.089	24.38	5.00
Middle 0.0m	29 May 07	no value *	0.145	46.49	6.50
Middle 1.5m	07 March 07	1.337	0.138	23.47	50.90
Middle 1.5m	23 March 07	1.047	0.138	15.19	12.50
Middle 1.5m	04 April 07	0.953	0.129	35.72	20.00
Middle 1.5m	16 April 07	1.108	0.149	26.70	21.25
Middle 1.5m	02 May 07	1.012	0.116	26.90	30.00
Middle 1.5m	14 May 07	no value *	0.107	25.78	8.00
Middle 1.5m	29 May 07	no value *	0.152	53.60	8.50
Middle 3.0m	07 March 07	1.198	0.126	18.45	51.35
Middle 3.0m	23 March 07	1.138	0.137	22.77	0.00
Middle 3.0m	04 April 07	0.973	0.131	27.17	22.50
Middle 3.0m	16 April 07	1.111	0.145	27.48	20.00
Middle 3.0m	02 May 07	0.989	0.124	33.86	36.25
Middle 3.0m	14 May 07	no value *	0.118	32.27	8.50
Middle 3.0m	29 May 07	no value *	0.138	30.09	3.50
North	07 March 07	0.852	0.093	13.19	50.65
North	23 March 07	1.003	0.088	14.13	16.25
North	04 April 07	1.090	0.144	16.80	17.50
North	16 April 07	1.049	0.141	25.57	13.12
North	02 May 07	1.119	0.120	38.75	31.88
North	14 May 07	no value *	0.106	10.05	6.50
North	29 May 07	no value *	0.121	31.74	3.50
South	07 March 07	1.197	0.133	14.17	50.68
South	23 March 07	1.251	0.146	16.13	10.00
South	04 April 07	0.991	0.108	14.84	22.50
South	16 April 07	1.006	0.138	32.32	10.63
South	02 May 07	1.047	0.126	29.37	38.75
South	14 May 07	no value *	0.085	11.81	7.50
South	29 May 07	no value *	0.142	42.88	2.50

* Defect at the nutrient analyses unit.

Table 5: Concentrations in Lake Ngaroto of NH_4-N [mg L^{-1}], NO_3-N [mg L^{-1}], PO_4-P [mg L^{-1}] at the three stations (north, middle and south), and the three depths in the middle station, at the surface and 1.5 and 3.0 m. See Figure 1 and Table 2 for the locations of the three stations.

Site	**Date**	**NH4** [m3 d-1]	**NO3** [mg L-1]	**PO4** [mg L-1]
Middle 0.0m	07 March 07	0.015	0.005	0.015
Middle 0.0m	23 March 07	0.019	0.018	0.020
Middle 0.0m	04 April 07	0.017	0.008	0.012
Middle 0.0m	16 April 07	0.017	0.007	0.009
Middle 0.0m	02 May 07	0.014	0.026	0.005
Middle 0.0m	14 May 07	0.010	0.000	0.005
Middle 0.0m	29 May 07	0.004	0.002	0.005
Middle 1.5m	07 March 07	0.018	0.014	0.016
Middle 1.5m	23 March 07	0.013	0.005	0.009
Middle 1.5m	04 April 07	0.018	0.004	0.010
Middle 1.5m	16 April 07	0.016	0.006	0.009
Middle 1.5m	02 May 07	0.040	0.031	0.009
Middle 1.5m	14 May 07	0.021	0.001	0.003
Middle 1.5m	29 May 07	0.005	0.005	0.005
Middle 3.0m	07 March 07	0.015	0.009	0.015
Middle 3.0m	23 March 07	0.014	0.010	0.006
Middle 3.0m	04 April 07	0.017	0.008	0.013
Middle 3.0m	16 April 07	0.017	0.004	0.009
Middle 3.0m	02 May 07	0.016	0.027	0.012
Middle 3.0m	14 May 07	0.025	0.001	0.004
Middle 3.0m	29 May 07	0.010	0.004	0.006
North	07 March 07	0.016	0.002	0.015
North	23 March 07	0.014	0.007	0.016
North	04 April 07	0.022	0.028	0.008
North	16 April 07	0.017	0.009	0.008
North	02 May 07	0.021	0.105	0.007
North	14 May 07	0.021	0.006	0.003
North	29 May 07	0.014	0.001	0.005
South	07 March 07	0.017	0.009	0.015
South	23 March 07	0.016	0.005	0.006
South	04 April 07	0.018	0.007	0.013
South	16 April 07	0.016	0.003	0.010
South	02 May 07	0.028	0.044	0.005
South	14 May 07	0.004	0.003	0.028
South	29 May 07	0.008	0.004	0.036

Table 6: Temperature [°C], concentrations of dissolved oxygen (DO) [mg L^{-1}], pH and conductivity [mS cm^{-1}] at the three stations (north, middle and south), and the three depths in the middle station, at the surface and 1.5 and 3.0 m. See Figure 1 and Table 2 for the locations of the three stations.

Site	**Date**	**Temperature** [°C]	**DO** [mg L^{-1}]	**pH**	**Conductivity** [µS cm^{-1}]
Middle 0.0m	07 March 07	23.77	10.12	8.47	167
Middle 0.0m	23 March 07	19.74	10.53	8.72	150
Middle 0.0m	04 April 07	20.77	9.35	7.84	154
Middle 0.0m	16 April 07	17.07	10.81	7.95	143
Middle 0.0m	02 May 07	16.86	9.69	7.85	141
Middle 0.0m	14 May 07	15.56	11.90	7.95	141
Middle 0.0m	29 May 07	13.51	10.58	7.63	134
Middle 1.5m	07 March 07	23.27	9.05	7.92	166
Middle 1.5m	23 March 07	19.61	10.48	8.56	149
Middle 1.5m	04 April 07	20.14	8.70	7.67	152
Middle 1.5m	16 April 07	16.72	9.90	7.67	142
Middle 1.5m	02 May 07	16.70	9.23	7.35	141
Middle 1.5m	14 May 07	14.97	10.86	7.95	139
Middle 1.5m	29 May 07	13.55	10.45	7.62	134
Middle 3.0m	07 March 07	22.63	3.55	7.17	167
Middle 3.0m	23 March 07	19.09	9.51	7.95	148
Middle 3.0m	04 April 07	19.72	7.64	7.41	151
Middle 3.0m	16 April 07	16.59	9.20	7.47	142
Middle 3.0m	02 May 07	16.45	7.89	7.16	142
Middle 3.0m	14 May 07	14.44	9.90	7.55	137
Middle 3.0m	29 May 07	13.45	10.47	7.59	134

Table 7: In-lake concentrations of phytoplankton species [cells mL^{-1}], recorded at the centre of Lake Ngaroto during the period from 07 March to 29 May 2007.

Species	**Cell densities [cells mL^{-1}] by sampling date**						
Cyanobacteria	**07 March 07**	**23 March 07**	**04 April 07**	**16 April 07**	**02 May 07**	**14 May 07**	**29 May 07**
Anabaena planktonica	43	67	9	33	10635	0	9078
Microcystis aeruginosa	0	0	0	0	0	1513	0
Microcystis flos aquae	727	0	0	0	0	0	98
Microcystis wesenbergii	15417	28507	10065	6951	8584	9191	9002
Total cyanobacteria [cells mL^{-1}]	**16187**	**28574**	**10074**	**6984**	**19219**	**10704**	**18178**
Diatoms							
Asterionella formoser	0	0	0	1	0	1	38
Aulacoseira distans	0	0	76	114	2	0	265
Aulacoseira granulata var. angustissima spiralis	17182	13424	16750	23207	16560	13617	19593
Aulacoseira granulata var. angustissima	0	2931	0	0	0	0	0
Aulacoseira granulata	4784	0	2393	3988	3447	1929	3404
Cyclotella sp.	0	218	3	152	1	0	76
Cymbella sp.	0	0	0	0	0	0	0
cf. *Navicula* sp.	0	0	0	38	76	0	0
Total diatoms [cells mL^{-1}]	**21966**	**16573**	**19222**	**27500**	**20086**	**15547**	**23376**
Total other							
Ceratium hirudinella	4	8	2	2	0	0	0
Closterium aciculare	2	9	76	3	2	0	0
Oocystis sp.	73	0	38	38	0	0	0
Pediastrum sp.	436	509	418	646	304	113	378
Peridinium sp.	582	73	76	4	2	4	3
Pandorina sp.	0	0	0	0	0	0	0
Scenedesmus communis	1	1	38	38	0	0	0
Staurastrum cingulum	73	1	2	2	0	0	0
Trachelomonas sp.	654	436	190	114	1	113	113
Sphaerocystis sp.	0	7	0	0	0	0	0
Total other [cells mL^{-1}]	**1825**	**1044**	**840**	**847**	**309**	**231**	**495**
Total [cells mL^{-1}]	**39978**	**46191**	**30136**	**35330**	**39613**	**26483**	**42049**

Appendix 2. Flow and water quality results provided by Waipa District Council

Location	Date	Flow [m³ d^{-1}]	NO_3 [mg L^{-1}]	NH_4 [mg L^{-1}]	TP [mg L^{-1}]
D1	29/8/2007	2419.2	2.62	0.09	0.091
D1	4/09/2007	0	1.68	0.06	0.084
D1	18/9/2007	0	1.6	0.07	0.089
D1	25/9/2007	0	1.37	0.08	0.135
D2	29/8/2007	1555.2	3.12	0.05	0.068
D2	4/09/2007	345.6	1.25	0.06	0.084
D2	18/9/2007	604.8	1.13	0.06	0.087
D2	25/9/2007	432	0.727	0.06	0.102
D13	29/8/2007	12182.4	1.86	0.17	0.178
D13	4/09/2007	7603.2	1.1	0.11	0.177
D13	18/9/2007	6480	0.327	0.01	0.248
D13	25/9/2007	10022.4	0.588	0.14	0.298
D14	29/8/2007	86227.2			
D14	4/09/2007	46396.8			
D14	18/9/2007	35078.4			
D14	25/9/2007	0			

Appendix 3. Physical data inputs and parameters used in the DYRESM- CAEDYM model

Table 8: Physical data inputs and parameters for DYRESM model.

Coefficient/variable	Value	Unit	Reference
Bulk aerodynamic momentum transport coefficient	0.0013		Stull (1988)
Mean albedo of water	0.08		
Emissivity of water surface	0.96		Imberger & Patterson (1981)
Critical wind speed	3.0	m s^{-1}	
Wind stirring efficiency	0.05		
Vertical mixing coefficient	10		
Shear production efficient	0.08		
Potential energy mixing efficiency	0.05		
Min/max layer thickness	0.2/0.4	m	
Light extinction coefficient (K_d)	0.4	m^{-1}	
Lake latitude	-37	°N	

Table 9: Dissolved oxygen (DO) and suspended solids (SS) parameters used in CAEDYM.

Parameter	Symbol	Unit	Value
DO parameters			
Temperature multiplier for sediment oxygen demand	V_{OP}	dimensionless	1.065
Half saturation constant for sediment oxygen exchange	K_{SOs}	mg L^{-1}	0.5
Static sediment oxygen exchange rate	R_{SOs}	g m^{-2} d^{-1}	1.5
SS parameters			
Composite resuspension rate	resusRate	g m^{-2} d^{-1}	0.28
Density of suspended solid particles	deS	kg m^{-3}	0.26500E+04
Diameter of suspended solids groups	diaSS	m	50000E-06
Critical shear stress (SS 1)	tcs	N m^{-2}	0.03000E+00
Critical shear stress (SS 2)	tcs	N m^{-2}	0.01500E+00