Nutrient budget and water balance for Lake Ngaroto

CBER Report 54

Report prepared for Waipa District Council

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Executive summary

The objectives of the present study were to provide an indication of tributary nutrient and sediment levels, and lake water quality for Lake Ngaroto over a period of summer sampling from December 2006 to February 2007. The measurements were designed to provide a foundation for a comprehensive water balance and nutrient load assessment for the lake in a future study, and to ultimately support informed decision making related to lake management.

Water samples were taken from three stations of Lake Ngaroto and its major tributaries on six occasions over summer 2006-7. Samples were analysed for both soluble (ammonium: NH_4-N, nitrate: NO_3-N, phosphate: PO_4-P), and total nutrient species (total phosphorus: TP, total nitrogen: TN), chlorophyll *a*, suspended solids, and, in the lake only, phytoplankton species composition. These measurements were repeated at three in-lake stations together with profiles of light (photosynthetically available radiation), temperature and conductivity.

Most inflows had little or no discharge on most occasions when samples were taken. It is suggested that groundwater makes up a major component of total tributary inflows to the lake. One inflow, MI 3 arising from Lake Ngarotoiti, was identified to be the dominant discharge to the lake and is considered to be of particular concern as it has very high levels of both total phosphorus (c. 0.3 mg L^{-1}) and total nitrogen (c. 2 mg L^{-1}), of which soluble nutrient species, representing bioavailable forms, make a high proportion.

The trophic state of Lake Ngaroto is in the category of 'super-trophic' or extremely enriched in nutrients on the basis of values of the 'Trophic Level Index', which is assessed on the basis of concentrations of total nitrogen, total phosphorus and chlorophyll *a*, and Secchi depth. Concentrations of suspended solids are also high and appear to be the dominant contributor to the low lake water clarity. Cyanobacteria are the dominant group of phytoplankton and their occurrence as surface blooms appears to be related to periods when the lake is stratified in warm, calm weather.

Management to improve water quality of Lake Ngaroto will be a major challenge given its current degraded state, and the likelihood that internal nutrient recycling and high sediment concentrations play an important role in maintaining the present state. A diversion of inflow MI3 may be useful in making an initial contribution to reducing the nutrient load to Lake Ngaroto but a full assessment must also take into account downstream effects. A strategy for pest fish removal would also be useful in order to reduce impacts of these fish on sediment-water exchanges. A more complete assessment of management strategies for the lake will be possible from a follow-up study which will provide a comprehensive water and nutrient budget for inflows to the lake and for the lake itself.

1 Introduction

The purpose of this study was to renew measurements of nutrients in Lake Ngaroro and complement these measurements with a suite of in-lake physical and biological measurements, as well as taking measurements of nutrient concentrations in tributary inflows and the outflow. By identifying major nutrient inputs into Lake Ngaroto and increasing understanding of the hydrology of the system it is possible to increase the probability of implementation of a successful lake management strategy.

Lake Ngaroto is a shallow, hypertrophic peat lake located south-west of Hamilton city and north-west of Te Awamutu. It is the largest of the Waipa peat lakes, with a surface area of 108 hectares (Environment Waikato 2006). The lake has several inlets and one outlet, controlled by an adjustable weir gate to allow water levels that are appropriate for recreational activities. One of the northern tributaries to Lake Ngaroto arises is from another smaller lake, Ngarotoiti.

Lake Ngaroto has been modified considerably from its original state. Water levels have been lowered since European settlement by the draining of peat soils and surrounding swampland for agriculture (Ministry for the Environment 2001; Faithfull *et al.* 2005), and the lake level is thought to have fallen by up to half a metre since the 1970s (Tony Roxburgh, pers. comm.). Furthermore, surface runoff and discharge from nearby Lake Ngarotoiti appear to important to the water balance, whereas subsurface flows are strongly dominant in natural peat lake systems (Faithfull *et al.* 2005). Farming run-off from the surrounding lake catchment is a dominant contributor to the external nutrient load to the lake, but resuspension of lakebed sediments contributes high water column turbidity and increases levels of nutrients (Ministry for the Environment 2001). It was evident in a preliminary survey of the tributary inputs to the lake that there are some major challenges involved in improving water quality of Lake Ngaroto (see Appendix A).

The hypertrophic status of Lake Ngaroto is typical of the current trophic status of many shallow Waikato peat lakes. The report ‘Snapshot of Lake Water Quality in New Zealand’ prepared by Opus International Consultants (Hamill & Lew 2006),

found, using trophic level indicators, that eight of fifteen shallow lakes monitored in the Waikato region are among the most eutrophic in the country. Lake Ngaroto was found to be hypertrophic based on monthly water quality sampling between September 1988 and June 1994 (Hamill & Lew 2006). Other hypertrophic peat lakes in the Waikato region include Mangahia, Mangakawhare, Rotokauri and Rotomanuka South, (Hamill & Lew 2006); Lake Ngarotoiti was not included in the analysis. Overall, shallow lakes (< 10 metres deep) were found to have poorer water quality, in terms of the trophic level indicators, than deeper lakes; to the extent that 90 percent of recorded hypertrophic lakes are shallow (Hamill & Lew 2006). It was suggested that shallow lakes, with a smaller volume and greater contact area of water with bottom sediments, lack the capacity to cope with increasing nutrient loading (Hamill & Lew 2006).

The ecological condition of the Waikato peat lakes is also generally poor. Lake Ngaroto rated less than 20 percent on the Lake SPI score of Clayton *et al.* (2002), indicating that vegetation within the lake and in the riparian margins is severely degraded from its natural state; the poor light climate in Lake Ngaroto means that there are no submerged aquatic plants. Lakes Rotokauri and Rotomanuka had similar ratings, while Lake Mangakawhare was the only Waikato peat lake to achieve a high rating for ecological condition (Hamill & Lew 2006).

Environment Waikato found no change in the trophic level of Lake Ngaroto during monitoring of shallow Waikato lakes between 1995 and 2001 (Barnes 2002). Chlorophyll *a* (chl *a*), total nitrogen (TN), total phosphorus (TP) and total suspended solids (SS) indicators did not change significantly over the study period (Barnes 2002). However, Secchi depth, total organic nitrogen (TON) and volatile suspended solids (VSS) were found to have deteriorated (Barnes 2002). Conversely, ammonium, nitrate and dissolved reactive phosphorus indicators were found to have improved (i.e. decreased), though concentrations of dissolved reactive phosphorus (DRP) were still considered to be high (Barnes 2002). To account for changes in nitrogen concentrations, and increases in VSS, Barnes (2002) suggested that a change occurred in the phytoplankton community structure during the study period. Decreases in bioavailable nutrient concentrations (i.e., ammonium, nitrate and dissolved reactive

phosphorus) should also be interpreted with caution and may simply reflect greater uptake into a larger prevailing phytoplankton biomass.

The monthly sampling regime performed by Environment Waikato also revealed seasonal fluctuations in four indicators used to reflect trophic status (Barnes 2002). Total phosphorus and phytoplankton biomass peaked in summer, whereas water clarity and TN were highest in winter (Barnes 2002). There was no change in TP through the sampling period while DRP concentrations were always variable with no apparent seasonal trend (Barnes 2002).

Lake Ngaroto also has a large number of exotic fish, including mosquito fish, catfish, rudd and koi carp, as well as native species such as bullies, short-fin eels and long-fin eels. Of concern is that benthic-feeding species such as catfish and koi carp disturb the lake bottom and reinforce wind transfer of sediments and nutrients from the bottom sediments to the water column. Many of the benthivorous exotic species, as well as rudd, and together with physical factors, are likely to collectively contribute to preventing the re-establishment of macrophytes

The present study comprised measurements of flow and nutrients in the major tributaries and the outflow of Lake Ngaroto, and measurements of temperature, phytoplankton concentrations and nutrients within the lake water. The study objectives were, first, to quantify the discharges and nutrient loads to Lake Ngaroto via the major surface tributaries using in-stream measurements.

2 Methods

2.1 Study sites

A series of sampling sites for inflows and within the lake were set up for the duration of the lake sampling. Figure 1 shows the main inflow sampling sites, the outflow sampling site, and the three lake sampling stations (North, Middle and South). Table 1 provides further details of the various stations, including their GPS locations.

Table 1: Abbreviations for in-lake samples sites and inflow and outflow sampling sites.

Site	Abbreviation	NZMG coordinates
Inlet 1	I1	2711801.03 E 6358607.49 N
Inlet2	I2	2711838.22 E 6358816.22 N
Main Inlet 3	MI3	2711170.65 E 6359061.80 N
Main Inlet 4	MI4	2711826.20 E 6357700.22 N
Inlet 5	I5	2710778.01 E 6358705.03 N
Inlet 6	I6	2710625.96 E 6358585.63 N
Inlet 11	I11	2710985.45 E 6357854.70 N
Inlet 12	I12	2711311.11 E 6357796.90 N
Outlet	Out	2711518.24 E 6359000.33 N
North site	North	2711010.13 E 6359068.05 N
Middle site	Middle	2711352.34 E 6358372.41 N
South site	South	2711632.21 E 6357958.10 N

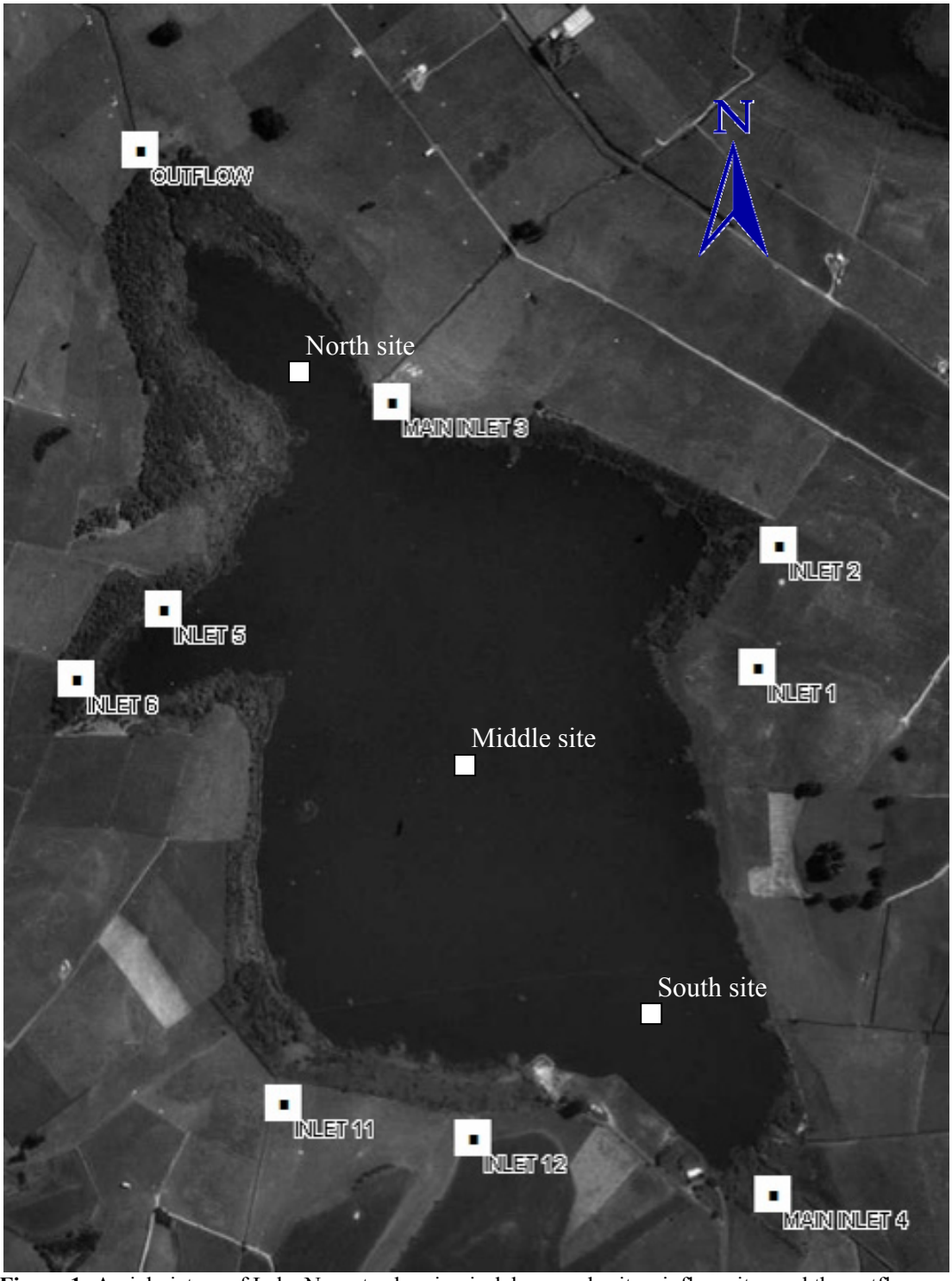

Figure 1: Aerial picture of Lake Ngaroto showing in-lake sample sites, inflow sites and the outflow.

2.2 Sampling

Samples were taken on six days over the 2006-2007 summer, on December 9 and 19 and January 9, 16, 25 and 30. Whenever possible, sampling was undertaken on both

the lake and the major tributaries on the same day, but with limitations due to lack of flow in some tributaries.

2.2.1 Lake

Water samples were collected with a Schindler-Patalas trap at three sites (Figure 1). Samples from sites in the south and in the north were collected from the surface of the lake and in the mid-lake site at depths of 0, 1.5 and 3.5 m, on December 9 and 19 and January 9, 16, 25 and 30.

Duplicate samples were filtered immediately after sampling using 0.45 µm GF/C filters in syringe tips, placed on ice in the dark for transportation, and frozen upon return to the laboratory. Samples were analysed for filterable nutrients, including ammonium (NH_4-N), nitrate (NO_3-N), nitrite (NO_2-N) and soluble reactive phosphorus (PO_4-P). Filter papers were placed on ice in the dark for transportation, and frozen on return to the laboratory for subsequent analysis of chlorophyll *a* concentration. Duplicate water samples were also collected, placed on ice and frozen for analysis of total phosphorus (TP) and total nitrogen (TN). Samples for suspended solids (SS) were taken in a 500 mL Schott bottle and stored on ice until return to the laboratory where they were stored at 4°C until analysis..

Unfiltered phytoplankton samples were taken from the middle site (Figure 1) of the lake at 0 metres depth on the 9 and 19 of December 2006 and the 9 and 16 of January 2007. Samples were preserved with 1 percent Lugol's solution and stored in the dark, immediately after collection until analysis.

Conductivity, pH, dissolved oxygen concentration and temperature were measured at 0.5m depth intervals, using a Yellow Springs Instruments 6000 Multi Parameter Sonde on 8, 19 December and 25, 30 January. On 9, 16, 30 January water column profiles of conductivity, temperature and depth were taken with a Sea Bird Electronics 19plus SEACAT Profiler (Sea-Bird Electronics Inc., Washington) with additional mounted sensors for simultaneous profiles of dissolved oxygen concentration (Sea-Bird Electronics, Inc.), photosynthetically available radiation

(PAR, Licor Inc.), beam transmittance (Sea-Bird Electronics, Inc.), and chlorophyll fluorescence (Chelsea Instruments Ltd).

Temperature loggers (Optic StowAway-Temp (C) from Onset) were installed at the mid-lake sampling site at depths of 0, 1.5 and 3 m on 19 December 2006 for a period of 42 days. Temperature was logged at half-hour intervals.

2.2.2 Inflows and outflow

Samples were collected at only eight inflow sampling stations, though there are around 22 inflows to the lake in total. The inflows outside of the eight sampled inflows had no detectable discharge over the sample period and can be categorised as mostly minor drains which contribute inflows only when the catchment is relatively saturated over winter.

All major flows were gauged using a Flow Mate flow meter on each sample day when streamflow was evident. Conductivity, pH, dissolved oxygen concentration and temperature were measured in the inflows using the Sonde probe. Water samples were collected from the tributaries for analysis 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. This value was used as a measure of water turbidity; higher values indicate high turbidity.

2.3.2 Nutrient analysis

Filterable nutrients were analysed 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 quantitatively reduced to nitrite by passage of 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.

Deionized 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 4ºC 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. The blank was subjected to the same procedural steps as samples. Ongoing precision and recovery were verified using a mid-range calibration standard every 20 to 30 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, are used to calculate the concentration of chlorophyll *a* in the sample extract:

$$C_{E,c} = F_s\left(r/r-1\right)\left(R_b - R_a\right) \tag{2.1}$$

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}:

$$C_{s,c} = \frac{C_{E,c} \times extract \quad volume \times DF}{sample \quad volume} \tag{2.2}$$

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

Dry weight of total suspended solids (SS) and particulate inorganic matter (PIM) were analysed in duplicate using filtration of samples onto pre-combusted (450 °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 solids concentrations (SS) were determined from the change in filter weight and the volume of water filtered.

2.3.5 Phytoplankton

Prior to analysis, phytoplankton samples were inverted 12 times in 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 the base of a Utermöhl chamber where additional Lugol's solution was added to aid identification. The samples were then left to settle for several hours before examination with an Olympus Inverted Microscope. A preliminary count was undertaken over the central transect area under 400x magnification for common species, and a subsequent count over the entire chamber area under 200x magnification for rare species. Calculations of number of cells per millilitre of sample were based upon sample size in the chamber, chamber diameter and central transect area.

3 Results

3.1 Inflows and outflow

Results of streamflow discharges are provided in Figure 2 for all investigated inflows and for the outflow. Further details on inflow discharges are provided in Table 2. Of the eight major inflows, five had detectable discharge on all sampling days. Inflow MI3 was calculated to have a discharge of 31,104 m^3 d^{-1} on 19 December 2006 and this inflow was the only one to have conspicuous discharge on each of the sample days. Discharge in MI3 decreased to 6,048 m^3 d^{-1} on 9 January 2007 and to 950 m^3 d^{-1} on 16 January 2007 but increased again on 25 January 2007 to 1,901 m^3 d^{-1}. On 19 December 2006 the other major inflow, MI4, had the highest flow rate of all inflows on that day (12,960 m^3 d^{-1}) but by 16 January 2007 it had no detectable flow. The measurements at I11 peaked on 9 January 2007 at a discharge of 4,320 m^3 d^{-1} but no flow was detected in this inlet in latter samplings. The outlet only had detectable discharge only on 16 January 2007, recording 3196 m^3 d^{-1}.

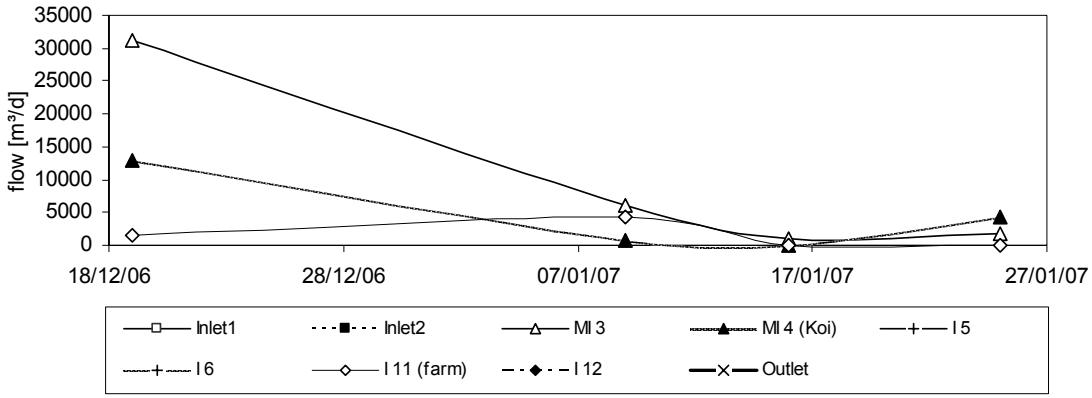

Figure 2: Discharge [m3 d^{-1}] in inflows and the outflow for the period 18 December 2006 to 27 January 2007. See Figure 1 for inflow and outflow locations and Table 1 for GPS locations.

Results of total phosphorus concentrations in inflows and the outflow are provided in Figure 3, with numerical values given in Table 2. Inflow MI3 generally had the highest concentration of total phosphorus, varying from a minimum of 0.19 mg L^{-1} on 9 January 2007 to a maximum of 0.365 mg L^{-1} on 16 January 2007. There was a peak in total phosphorus on all sampled inlets on 16 January 2007; peak concentrations also occurred for total nitrogen and chlorophyll *a*. Concentrations of total phosphorus

were also high in inflow MI4, with a peak of 0.24 mg L^{-1} on 16 January 2007. By contrast, inflow I6 had lower concentrations; 0.035 mg L^{-1}, but concentrations increased markedly on 16 January 2007 to a maximum of 0.18 mg L^{-1}. The outlet had relatively constant total phosphorus concentrations of approximately 0.1 mg L^{-1}, except for 25 January 2007 when the concentration was 0.19 mg L^{-1}. Inflows I1, I2, I5 and I12 had small discharges and generally had lower concentrations of total phosphorus.

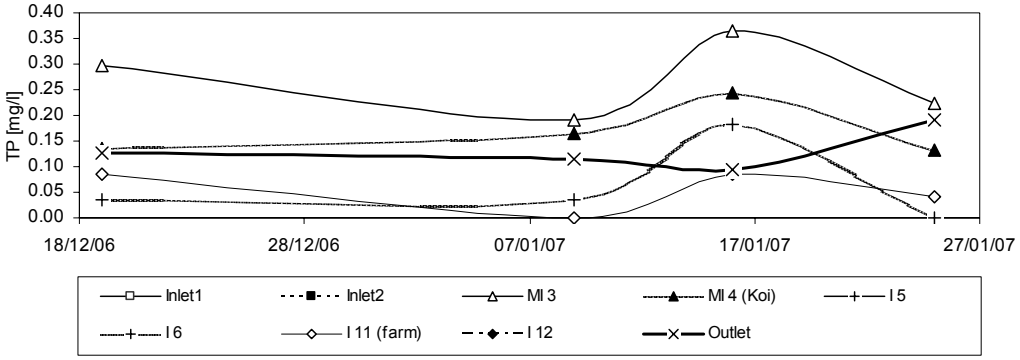

Figure 3: Concentrations of TP [mg L^{-1}] in inflows and the outflow of Lake Ngaroto. See Figure 1 for inflow and outflow locations and Table 1 for GPS locations.

Figure 4 shows the results for total nitrogen concentrations for all measured inflows and for the outflow, with numerical values provided in Table 2. Total nitrogen concentrations were only measured in inflows I1, I2 and I11 on 19 December 2006, yielding values of 1.64, 2.69 mg L^{-1} and 1.4 mg L^{-1}, respectively. Inflows MI3 and M14 were sampled on each day and showed similar concentrations, in the range 1.5 to 2.58 mg L^{-1}. No measurements of total nitrogen were made for inflow I12. In the outlet, concentrations of total nitrogen ranged from 0.71 mg L^{-1} on 9 January 2007 to 1.57 mg L^{-1} on 25 January 2007.

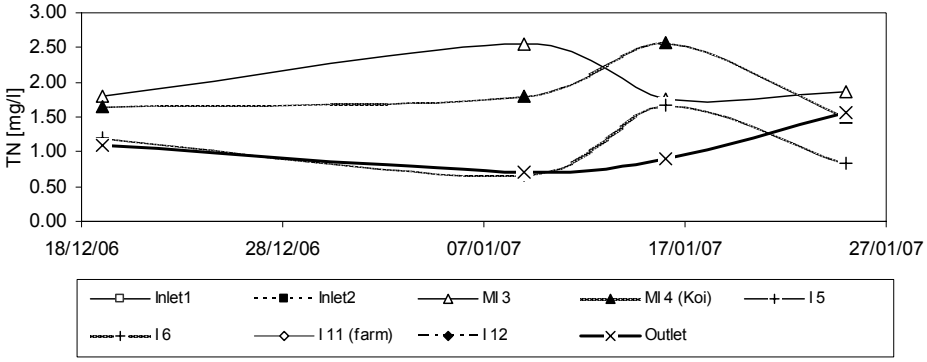

Figure 4: Concentrations of TN [mg L^{-1}] in inflows and the outflow of Lake Ngaroto. See Figure 1 for inflow and outflow locations and Table 1 for GPS locations.

Results of chl *a* concentration are provided in Figure 5 and details for the individual sites and sample times are given in Table 2. Relatively few measurements were made of chl *a* concentrations in inflows as discharges and concentrations were not considered to *directly* influence chlorophyll *a* concentrations in the lake, though the possibility of 'seeding' of specific phytoplankton species from slow-flowing stream and wetland areas around the lake should not be discounted. It is notable that inflows MI3 and MI4 had quite high chl *a* concentrations on some sampling occasions, notably MI4 with a concentration of 65.4 µg l^{-1} on 19 December 2006. Concentrations of chl *a* in inflow I11 were measured only twice, yielding 1.2 µg l^{-1} on 19 December 2006 and 21 µg l^{-1} on 16 January 2007. In the outlet, chlorophyll *a* concentrations varied from as low as 8.3 µg l^{-1} on 9 January 2007 to as high as 52.4 µg l^{-1} on 25 January 2007.

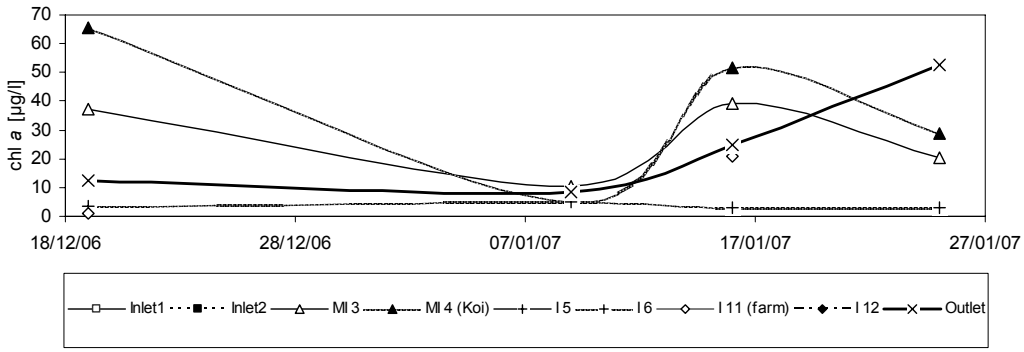

Figure 5: Concentrations of chl *a* [µg L^{-1}] in inflows and the outflow of Lake Ngaroto. See Figure 1 for inflow and outflow locations and Table 1 for GPS locations.

Results of suspended solids (SS) concentrations from the inflows and from the outflow are provided in Figure 6. Relatively few samples were taken for SS in inflows I1, I2, I5 and I11 (see Table 2). Concentrations in MI3 over four sample dates varied from 4 mg L^{-1} on 16 January 2007 to 15 mg L^{-1} on 19 December 2006. Inflow MI4 consistently had the highest SS concentrations, with a peak up to 47.5 mg L^{-1} on 19 December 2006. Concentrations in inflow I6 varied from only 5 to 10 mg L^{-1}. The concentration range in the outlet varied considerably, from as low as 6 mg L^{-1} on 16 January 2007 up to 46 mg L^{-1} on 25 January 2007.

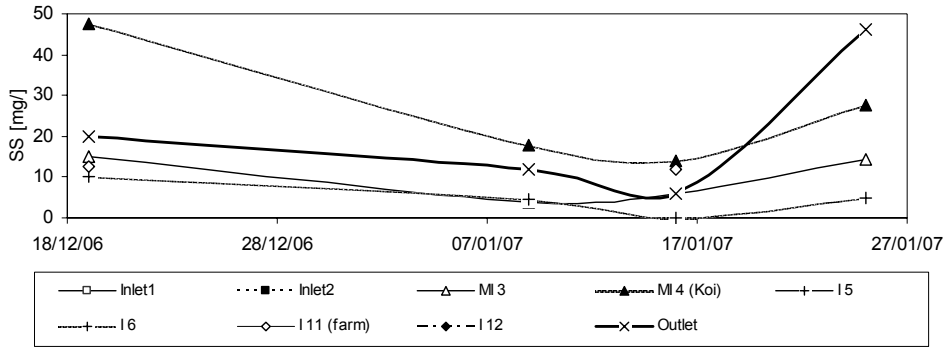

Figure 6: Concentrations of SS [mg L^{-1}] in inflows and the outflow of Lake Ngaroto. See Figure 1 for inflow and outflow locations and Table 1 for GPS locations.

Ammonium concentrations in the inflows were generally < 0.1 mg L^{-1} though four samples on 19 December 2006 had concentrations > 0.20 mg L^{-1}. Inflow MI3 generally had the highest concentration of NH_4-N, from a minimum of 0.07 mg L^{-1} on 19 December 2006 to a maximum of 0.21 mg L^{-1} on 09 January 2006. Inflows I2, MI4, I5, I6, I11 and I12 had lower concentrations of NH_4-N, generally < 0.05 mg L^{-1}. A peak in NH_4-N of 0.20 mg L^{-1} occurred in the outflow on 16 January 2006.

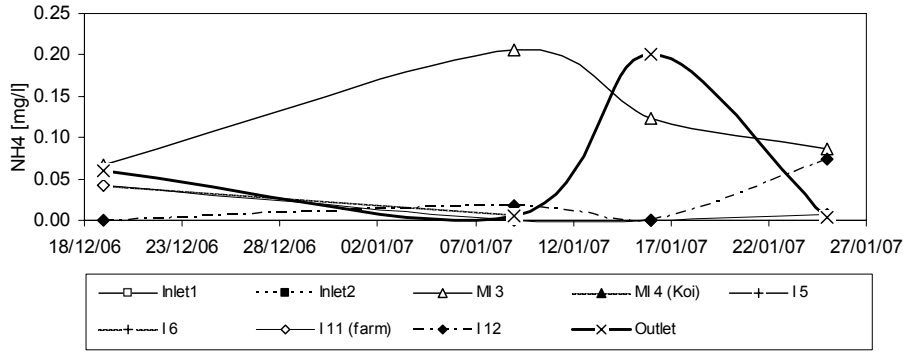

Figure 7: Concentrations of NH_4-N [mg L^{-1}] in inflows and the outflow of Lake Ngaroto. See Figure 1 for inflow and outflow locations and Table 1 for GPS locations.

Inlet MI3 generally had the highest concentration of nitrate (NO_3-N), from a minimum of 0.29 mg L^{-1} on 16 January 2007 to a maximum of 0.97 mg L^{-1} on 9 January 2007. Concentrations of NO_3-N were high across most stations on 19 December 2006 relative to other days. The outflow had concentrations of NO_3-N consistently < 0.05 mg L^{-1} during the study period.

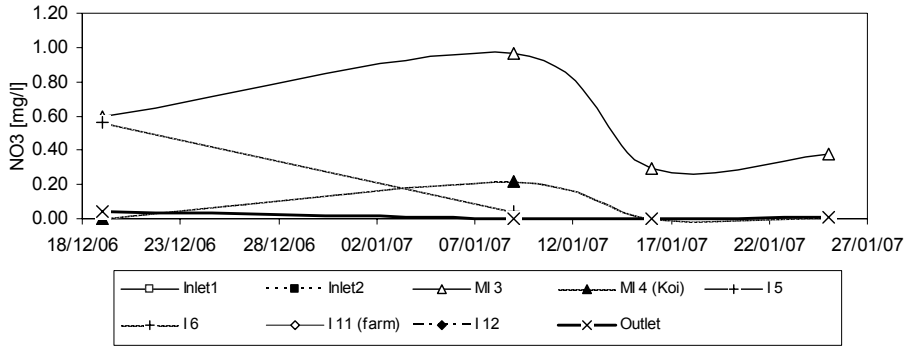

Figure 8: Concentrations of NO_3-N [mg L^{-1}] in inflows and the outflow of Lake Ngaroto. See Figure 1 for inflow and outflow locations and Table 1 for GPS locations.

Concentrations of soluble reactive phosphorus (PO_4-P) were consistently high in inflow MI3, varying from 0.010 mg L^{-1} on 9 January 2007 to 0.060 mg L^{-1} on 16 January 2007. Inflow MI4 had uniformly low concentrations of PO_4-P, averaging 0.004 mg L^{-1}. The peak concentration in the outflow occurred on 16 January 2007 at 0.022 mg L^{-1} and the minimum occurred soon after, at 0.002 mg L^{-1} on 25 January 2007.

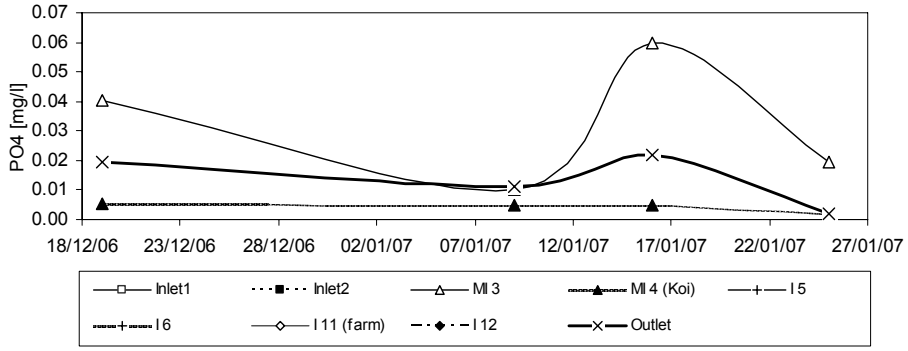

Figure 9: Concentrations of PO_4-P [mg L^{-1}] in the inflows and outflow of Lake Ngaroto. See Figure 1 for inflow and outflow locations and Table 1 for GPS locations.

Table 2: Values for flow [m^3 d^{-1}], TN [mg L^{-1}], TP [mg L^{-1}], Chl *a* [µg L^{-1}] and SS [mg L^{-1}] for the inflows and outflow of Lake Ngaroto. See Figure 1 and Table 1 for the locations of the inflows and the outflow. Symbol (-) is no data recorded but values of zero refer to actual measurements.

Site	Date	Flow [m^3 d^{-1}]	TN [mg L^{-1}]	TP [mg L^{-1}]	Chl *a* [µg L^{-1}]	SS [mg Ll^{-1}]
I1	19 December 2006	0	1.64	0.08	-	-
	09 January 2007	0	-	-	-	-
	16 January 2007	0	-	-	-	-
	25 January 2007	0	-	-	-	-
I2	19 December 2006	0	2.69	0.17	-	-
	09 January 2007	0	-	-	-	-
	16 January 2007	0	-	-	-	-
	25 January 2007	0	-	-	-	-
MI3	19 December 2006	31104	1.79	0.30	37.4	15
	09 January 2007	6048	2.55	0.19	10.5	4
	16 January 2007	950.4	1.75	0.37	39.2	6
	25 January 2007	1900.8	1.86	0.22	20.2	14
MI4	19 December 2006	12960	1.64	0.13	65.4	-
	09 January 2007	864	1.79	0.17	4.9	-
	16 January 2007	0	2.58	0.24	51.4	-
	25 January 2007	4320	1.50	0.13	28.9	-
I5	19 December 2006	0	1.20	0.02	2.1	5
	09 January 2007	0	-	-	-	-
	16 January 2007	0	-	-	-	-
	25 January 2007	0	-	-	-	-
I6	19 December 2006	0	1.21	0.04	3.7	10
	09 January 2007	0	0.67	0.04	4.9	5
	16 January 2007	0	1.67	0.18	3.0	-
	25 January 2007	2764.8	0.84	0	3.1	5
I11	19 December 2006	1468.8	1.40	0.08	1.2	12.5
	09 January 2007	4320	-	-	-	-
	16 January 2007	0	-	0.09	21	12
	25 January 2007	0	-	0.04	-	-
I12	19 December 2006	0	-	-	-	-
	09 January 2007	0	-	0.09	1.5	7
	16 January 2007	0	-	-	-	-
	25 January 2007	0	-	-	-	-
Out	19 December 2006	0	1.09	0.13	12.5	20
	09 January 2007	0	0.71	0.12	8.3	12
	16 January 2007	3196.8	0.91	0.09	24.8	6
	25 January 2007	0	1.57	0.19	52.4	46

Table 3: 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 1 for the locations of the inflows and the outflow. The symbol (-) means no data recorded but values of zero refer to actual measurements.

Site	Date	NH_4 [mg L^{-1}]	NO_3 [mg L^{-1}]	PO_4 [mg L^{-1}]
I1	19 December 2006	0.20	0.33	0.0147
	09 January 2007	-	-	-
	16 January 2007	-	-	-
	25 January 2007	-	-	-
I2	19 December 2006	0.01	0.42	0.0046
	09 January 2007	-	-	-
	16 January 2007	-	-	-
	25 January 2007	-	-	-
MI3	19 December 2006	0.07	0.60	0.0406
	09 January 2007	0.21	0.97	0.0103
	16 January 2007	0.12	0.29	0.0599
	25 January 2007	0.09	0.38	0.0194
MI4	19 December 2006	0.01	0.00	0.0053
	09 January 2007	0.02	0.21	0.0048
	16 January 2007	0.01	0.00	0.0048
	25 January 2007	0.00	0.01	0.0020
I5	19 December 2006	0.01	0.64	0.0111
	09 January 2007	-	-	-
	16 January 2007	-	-	-
	25 January 2007	-	-	-
I6	19 December 2006	0.04	0.56	0.0079
	09 January 2007	0.01	0.04	0.0048
	16 January 2007	-	-	-
	25 January 2007	-	-	-
I11	19 December 2006	0.04	0.70	0.0376
	09 January 2007	0.00	-	-
	16 January 2007	0.00	-	-
	25 January 2007	0.01	-	0.0180
I12	19 December 2006	0.00	-	-
	09 January 2007	0.02	0.21	0.0277
	16 January 2007	0.00	-	-
	25 January 2007	0.07	0.22	0.0104
Out	19 December 2006	0.06	0.04	0.0196
	09 January 2007	0.01	0.00	0.0110
	16 January 2007	0.20	0.00	0.0221
	25 January 2007	0.00	0.00	0.0022

3.2 Lake results

Five separate lake samples were used for determination of nutrient and chl *a* concentrations in Lake Ngaroto, including three stations (north, middle and south), and collection of three samples in the middle station, at the surface and 1.5 and 3.5 m depth. Results of the TP concentrations measured in the lake are shown in Figure 10. Total phosphorus concentrations were relatively consistent on each sample day and over the investigation period, averaging 0.18 mg L^{-1} for the entire sample group. Concentrations of TP ranged from 0.10 mg L^{-1} on 9 December 2006 in the middle of the lake at depths of 1.5 and 3.5 m, to 0.21 mg l^{-1} on 19 December 2006 in the middle of the lake at a depth of 3.5 m as well as on 25 January 2007 in the middle of the lake at a depth of 3.5 m and in the south of the lake.

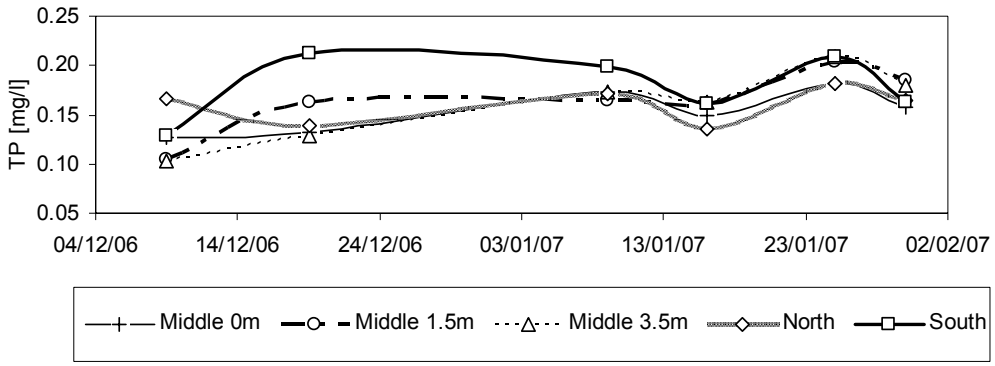

Figure 10: Concentrations for TP [mg L^{-1}] for the five sampling sites in Lake Ngaroto for the period 9 December 2006 to 30 January 2007.

Results of TN concentrations measured during the sample period are provided in Figure 11. The highest recorded TN concentration was 2.35 mg L^{-1} in the south of the lake on 19 December 2006, and the lowest was 1.27 mg L^{-1} on 9 December in the middle of the lake at a depth of 3.5 m. The south of the lake generally had higher concentrations, averaging 1.82 mg L^{-1} for the entire sample period, which was 0.2 mg L^{-1} greater than the average of 1.62 mg L^{-1} for all stations.

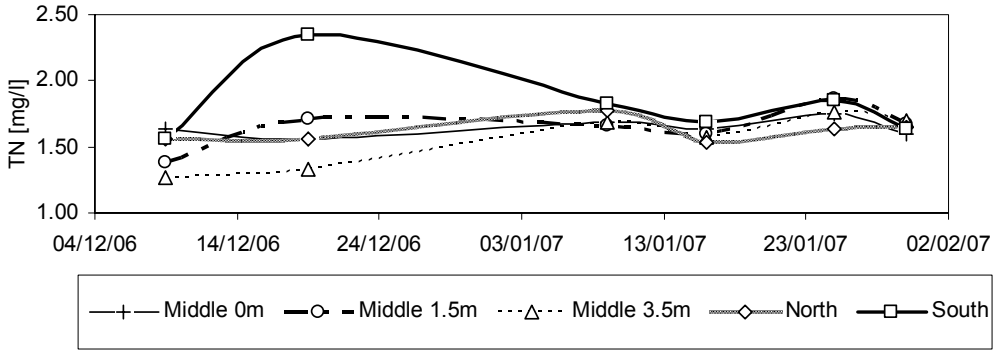

Figure 11: Concentrations for TN [mg L^{-1}] for the five sampling sites in Lake Ngaroto for the period 9 December 2006 to 30 January 2007.

Concentrations of chl *a* over the six sample dates varied from 80 µg L^{-1} on 19 December 2006 in the south of the lake to 4.7 µg L^{-1} on 9 January 2007 in the north of the lake (Figure 12). There was a marked increase in chl *a* concentrations in the south of the lake between 9 December 2006 (22 µg L^{-1}) and 19 December 2007 (80 µg L^{-1}). Similarly, chl *a* increased from 6.0 µg L^{-1} on 9 January 2007 to 76.6 µg l^{-1} on 25 January 2007. Concentrations in the north of the lake were consistently at the lower limit of the range observed on each sample day but there was otherwise little pattern to the spatial or temporal distribution of chl *a*.

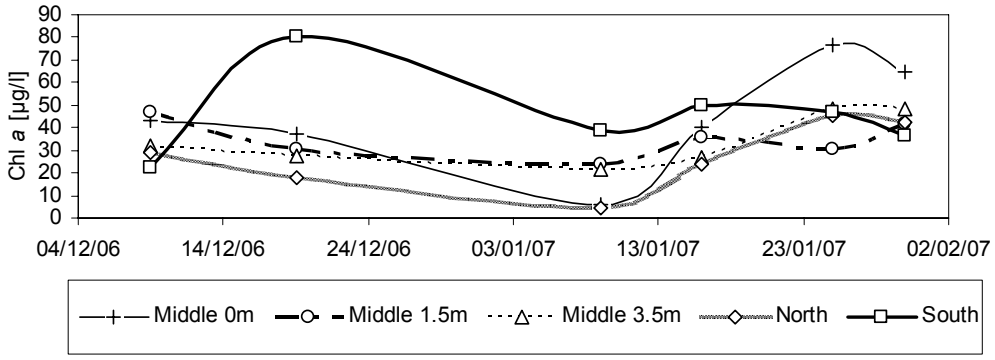

Figure 12: Concentrations for chl *a* [µg L^{-1}]for the five sampling sites in Lake Ngaroto for the period 9 December 2006 to 30 January 2007.

Figure 13 shows clearly the similarity of concentrations of SS across the three stations. Mean concentrations over the three stations on each sample day were 42 mg L^{-1} on 19 December 2006, 30.5 mg L^{-1} on 9 January 2007, 16.4 mg L^{-1} on 16 January, 60.4 mg L^{-1} on 25 January 2007 and 74.6 mg L^{-1} on 30 January 2007.

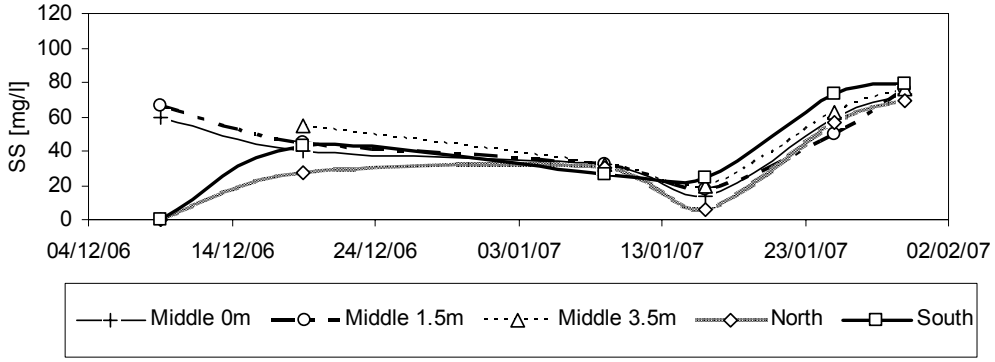

Figure 13: Concentrations SS [mg L^{-1}] concentrations for the five sampling sites in Lake Ngaroto for the period 9 December 2006 to 30 January 2007.

Ammonium concentrations at the three stations (north, middle and south) as well as at the three depths in the middle (surface, 1.5 and 3.5 m) were relatively uniform and generally low on each sample day with one exception, on 19 December 2006, when concentrations at the south station were low compared with all other samples taken on that day (Figure 14).

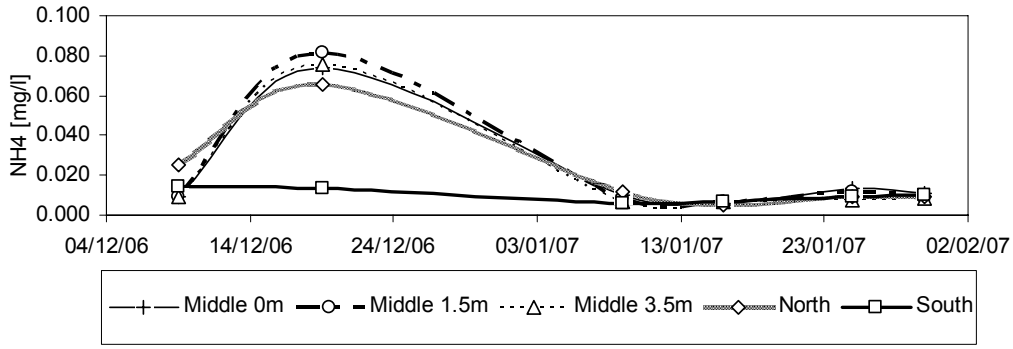

Figure 14: Concentrations NH_4-N [mg L^{-1}] for the five sampling sites in Lake Ngaroto for the period 9 December 2006 to 30 January 2007.

Table 4: In-lake concentrations for TN [mg L^{-1}], TP [mg L^{-1}], Chl *a* [µg L^{-1}] and 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 3.5 m. See Figure 1 and Table 1 for the locations of the three stations. The symbol (-) corresponds to no data recorded but values of zero refer to actual measurements.

Site	Date	TN [mg L^{-1}]	TP [mg L^{-1}]	Chl *a* [µg L^{-1}]	SS [mg L^{-1}]
Middle 0,0m	09 December 2006	1.63	0.13	43.0	60.0
	19 December 2006	1.56	0.13	36.9	40.0
	09 January 2007	1.69	0.17	6.0	32.0
	16 January 2007	1.63	0.15	40.3	14.0
	25 January 2007	1.75	0.18	76.6	60.0
	30 January 2007	1.59	0.16	64.4	73.0
Middle 1,5m	09 December 2006	1.38	0.10	47.0	66.0
	19 December 2006	1.71	0.16	30.6	45.0
	09 January 2007	1.66	0.16	23.7	32.0
	16 January 2007	1.60	0.16	35.4	18.0
	25 January 2007	1.86	0.20	30.3	50.0
	30 January 2007	1.67	0.18	41.3	76.0
Middle 3,5m	09 December 2006	1.27	0.10	32.0	-
	19 December 2006	1.33	0.13	27.6	55.0
	09 January 2007	1.68	0.17	21.7	32.0
	16 January 2007	1.58	0.16	26.6	20.0
	25 January 2007	1.76	0.21	48.7	62.5
	30 January 2007	1.70	0.18	48.0	76.0
North	09 December 2006	1.56	0.17	29.0	< 2
	19 December 2006	1.56	0.14	17.6	27.5
	09 January 2007	1.78	0.17	4.7	30.3
	16 January 2007	1.53	0.14	24.1	6.0
	25 January 2007	1.63	0.18	45.03	56.5
	30 January 2007	1.65	0.17	42.70	69.0
South	09 December 2006	1.56	0.13	22.00	< 2
	19 December 2006	2.35	0.21	79.99	42.0
	09 January 2007	1.83	0.20	38.68	26.0
	16 January 2007	1.69	0.16	49.90	24.0
	25 January 2007	1.86	0.21	46.96	73.0
	30 January 2007	1.64	0.16	36.60	79.0

Nitrate concentrations were consistently low (around 0.005 mg L^{-1}) except for the first sample day on 9 December 2006 when concentrations at most stations were maximal for the sampling period and the south station was as high as 0.021 mg L^{-1}. From Figures 13 and 14 it is evident that inorganic nitrogen concentrations are consistently

low in the lake with the exception of 9 December when there most samples showed elevated concentrations of NH_4-N.

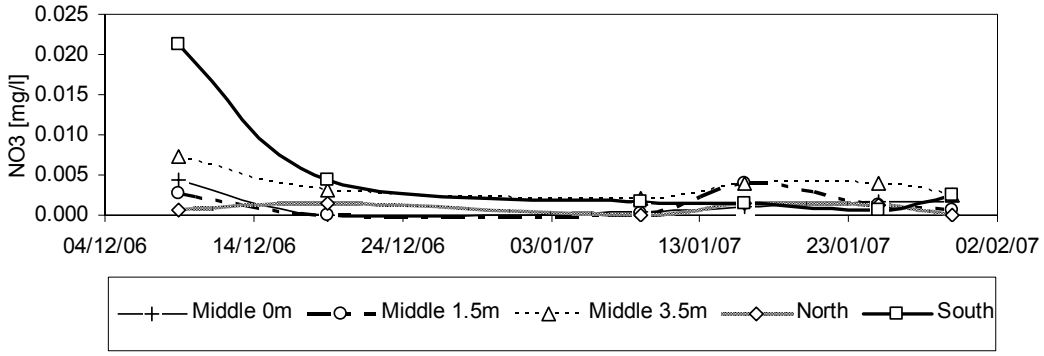

Figure 15: Concentrations NO_3 [mg L^{-1}] for the five sampling sites in Lake Ngaroto for the period 9 December 2006 to 30 January 2007.

Phosphate concentrations in the lake were generally in the range 0.001 to 0.02 mg L^{-1}, with exceptions on 9 December 2006 in the north of the lake (0.046 mg L^{-1}) and on 16 January 2007 in middle lake in a depth of 1.5m (0.064 mg L^{-1}) (Figure 16). Phosphate concentrations are otherwise mostly low and close to detection limits.

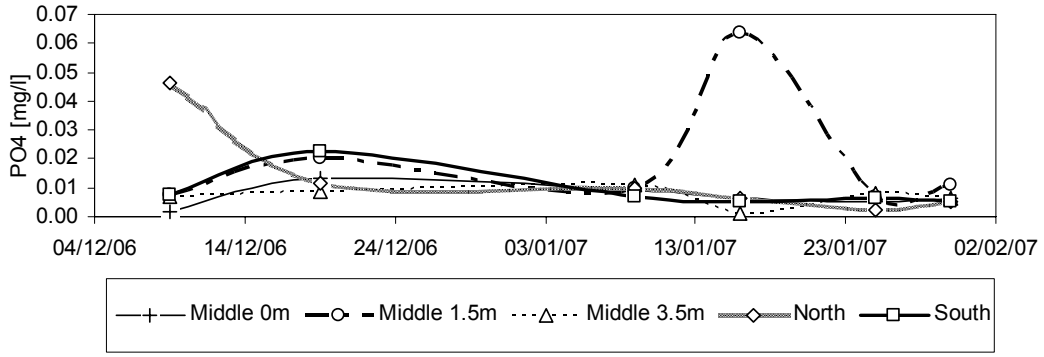

Figure 16: Concentrations PO_4 [mg L^{-1}] for the five sampling sites in Lake Ngaroto for the period 9 December 2006 to 30 January 2007.

Despite the shallow nature of Lake Ngaroto, the lake can undergo periods of diurnal stratification, particularly in January (days 13 to 43 of Figure 17). During this month

temperatures at the middle station can be as high as 29 °C at a time when the temperature at 3.5 m is only 23 °C. There is also a wide diurnal variability of temperature at this time, with concentrations at the surface tending to approximate the relatively constant temperature at depth of 3.5 m, and therefore varying by as much as 6 °C.

Between periods of stratification there were several days when temperatures were homogeneous, with diurnal variations typically of the order of 1 °C. Average water column temperature increased over the course of the study, from as low as c. 20 °C soon after commencement of sampling to around 25 °C at the end of sampling.

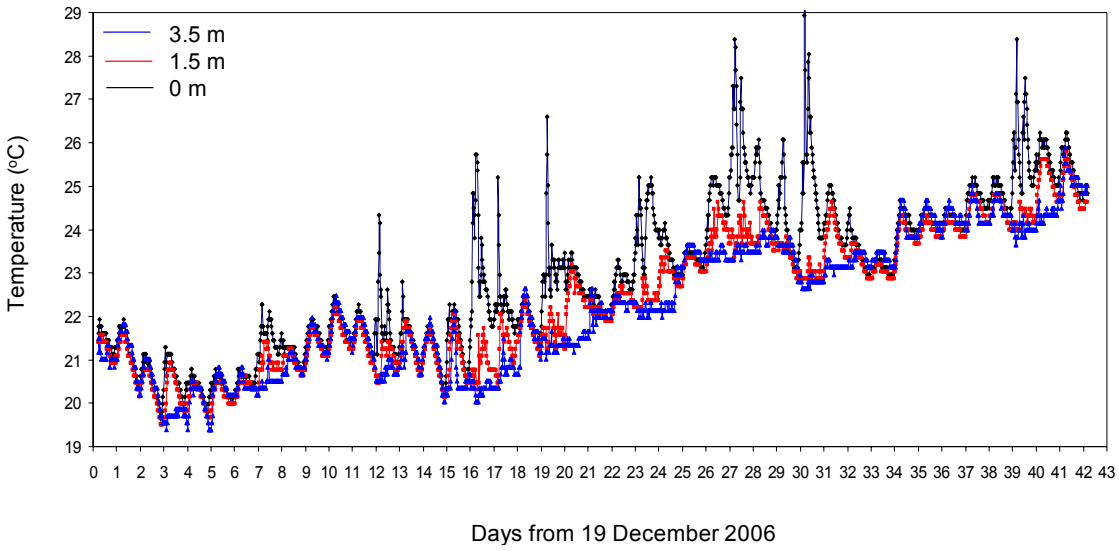

Figure 17: Temperature in the middle of the lake at three depths, surface (0 m), 1.5 m and 3.5 m, for the period 19 December 2006 to 29 January 2007.

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 3.5 m. See Figure 1 and Table 1 for the locations of the three stations. The symbol (-) means no data recorded but values of zero refer to actual measurements.

Site	**Date**	**NH_4** [mg L^{-1}]	**NO_3** [mg L^{-1}]	**PO_4** [mg L^{-1}]
Middle 0.0m	09 December 2006	0.009	0.004	0.0016
	19 December 2006	0.074	0.000	0.0131
	09 January 2007	0.010	0.000	0.0092
	16 January 2007	0006	0001	0.0065
	25 January 2007	0.013	0.002	0.0054
	30 January 2007	0.011	0.002	0.0064
Middle 1.5m	09 December 2006	0.009	0.003	0.0073
	19 December 2006	0.082	0.000	0.0205
	09 January 2007	0.009	0.000	0.0099
	16 January 2007	0.006	0.004	0.0638
	25 January 2007	0.012	0.001	0.0071
	30 January 2007	0.008	0.001	0.0111
Middle 3.5m	09 December 2006	0.009	0.007	0.0069
	19 December 2006	0.076	0.003	0.0084
	09 January 2007	0.007	0.002	0.0112
	16 January 2007	0.007	0.004	0.0009
	25 January 2007	0.008	0.004	0.0078
	30 January 2007	0.008	0.002	0.0061
North	09 December 2006	0.025	0.001	0.0465
	19 December 2006	0.066	0.001	0.0114
	09 January 2007	0.012	0.000	0.0100
	16 January 2007	0.005	0.002	0.0066
	25 January 2007	0.009	0.001	0.0024
	30 January 2007	0.009	0.000	0.0054
South	09 December 2006	0.014	0.021	0.0074
	19 December 2006	0.013	0.004	0.0228
	09 January 2007	0.006	0.002	0.0069
	16 January 2007	0.007	0.001	0.0053
	25 January 2007	0.009	0.001	0.0063
	30 January 2007	0.010	0.002	0.0051

Vertical temperature profiles (Figure 18A) are a 'snapshot' of data presented in Figure 17, and show values for each sampling day in the middle station around 1000 hr. They generally reveal that the lake was well mixed or weakly stratified. Temperature at the surface ranged from 20.8 °C on 8 December 2006 to 24.2 °C on 30 January 2007. At the bottom, temperature ranged from 20.4 °C on 19 December 2006 to 24.2 °C on 30 January 2007.

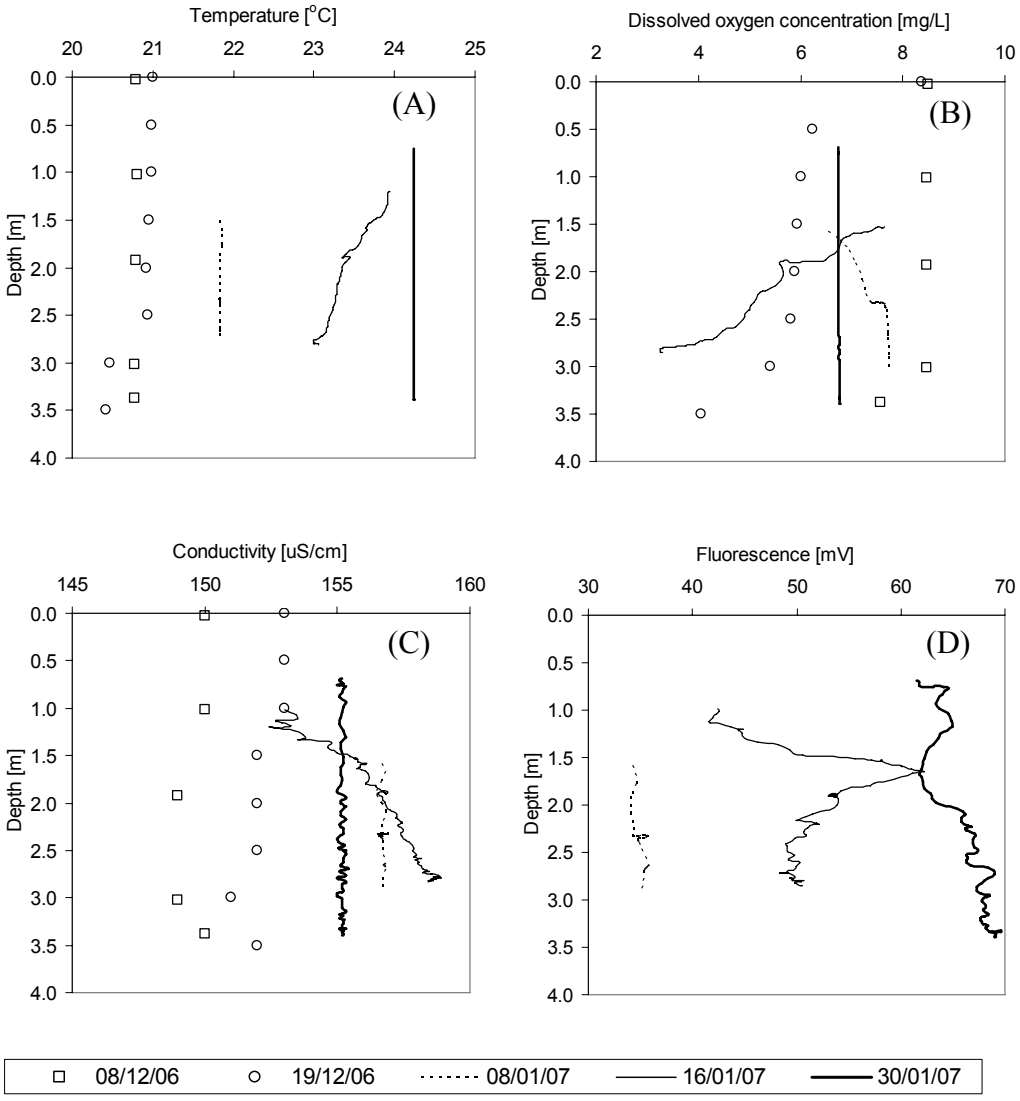

Figure 18: Vertical profiles of (A): Temperature [°C], (B): dissolved oxygen concentration [mg L^{-1}], (C): conductivity [µS cm^{-1}], and (D): fluorescence [mV] for all sampling days. Dots indicate readings taken with YSI sonde and lines indicate CTD profiles.

Dissolved oxygen concentrations were as low as 3.2 mg L^{-1} at the bottom of the lake on 16 January 2007, while the maximum recorded value was 8.5 mg L^{-1} at the surface

on 8 December 2006 (Figure 18B). Gradients of dissolved oxygen were quite marked on three sampling days, decreasing rapidly with depth on 8 and 19 December 2006 and 16 January 2007, while on 30 January 2007 the distribution of oxygen was nearly homogeneous through the water column when the temperature profile was also homogeneous. Conductivity varied between 149 μS cm^{-1} on 8 Dec 2006 and 163 μS cm^{-1} on 8 Jan 2007 (Figure 18C). There was little vertical variation in conductivity on most days except for a general linear tendency of increasing conductivity with depth on 16 January 2007, when temperature also showed a similar but reverse trend with depth (Figure 19A). Fluorescence profiles, used here as an analogue for chlorophyll *a* concentrations, were taken on three days in 2007 when profiles were taken with the Seabird CTD. These profiles reinforce the general trend of increasing chlorophyll *a* observed in the three water samples taken at the middle station at three depths (Figure 12). Mean water column fluorescence values were as low as 35 mV on 8 January 2007 to as high as 66 mV on 30 Jan 2007. Our previous findings of an approximate 1:1 dependence of chlorophyll *a* concentrations in μg L^{-1} and fluorescence values in mV is borne out in comparison of Figure 12 against Figure 18A.

Values of photosynthetically available radiation obtained from the Seabird CTD casts were used to compute the water column light attenuation coefficient, k_d. Values of k_d on the three sample days, 9, 16 and 30 January 2007, are reasonably consistent at just over 7 m^{-1} (Table 6). These values correspond to a euphotic depth of around only 0.65 m, i.e., dominance of photosynthesis over radiation during daytime is likely to be confined to the upper 0.65 m of the water column.

Table 6: k_d [m^{-1}] for Lake Ngaroto during the investigation period 9 January to 30 January 2007.

Site	Date	k_d [m^{-1}]
Middle	09 January 2007	7.26
Middle	16 January 2007	7.43
Middle	30 January 2007	7.60

The dominant species of phytoplankton in samples were *Aulacoseira* and *Pediastrum*, but blue-green genera, *Microcystis* and *Anabaena* in particular, were generally most dominant. *Closterium aciculare,* and *Cyclotella sp.*, *Dictyosphaerium sp.*, *Peridinium sp.* and *Trachelomonas sp.* were also encountered at low to moderate denisities. A full species list and their concentrations are given in Table 7.

Table 7: In-lake concentrations of phytoplankton species [cells mL^{-1}], recorded at the centre of the lake on the first four sampling days

Species	**Cell counts [cells mL^{-1}] by sampling date**			
	09 Dec 2006	**19 Dec 2006**	**09 Jan 2007**	**16 Jan 2007**
Anabaena planktonica	4384	2273	5010	4928
Anabaena cf. *spiroides*	90	0	0	0
Microcystis aeruginosa	1550	18372	250	0
Microcystis flos aquae	2275	1099	3640	38
Microcystis wesenbergii	2745	0	103500	3182
Unknown cyanobacterium	0	38	0	0
Total cyanobacteria [cells/mL]	**11044**	**21782**	**112400**	**8148**
Aulacoseira granulata var. angustissima spiralis	3108	10038	7424	5114
Aulacoseira *granulata var. angustissima*	33	0	17	0
Aulacoseira granulata	17	152	0	95
Ceratium sp.	10	0	2	0
Closterium aciculare	82	170	8	57
Cyclotella sp.	0	152	0	76
Cymbella sp.	1	0	0	0
Dictyosphaerium sp.	80	0	136	0
Epithemia sp.	1	19	0	19
Eudorina sp.	16	0	64	0
Nitzschia sp.	1	0	0	0
Oocystis sp.	30	19	0	0
Pandorina sp.	124	0	0	0
Pediastrum spp.	128	304	192	11515
Peridinium sp.	51	38	114	0
Pinnularia sp.	3	1	0	0
Rhopalodia sp.	2	0	2	0
Scenedesmus communis	0	0	6	0
Sphaerocystis sp.	16	0	0	0
Staurastrum cingulum	18	19	5	0
Trachelomonas sp.	2	19	2	189
Total other [cells/mL]	**3723**	**10931**	**7972**	**17065**
Total [cells/mL]	**14767**	**32713**	**120372**	**25213**

The balance between concentrations of cyanobacteria and other algae was similar on both December sampling days, although concentrations of *Aulacoseira granulata var. angustissima spiralis* and *Microcystis aeruginosa* were an order of magnitude higher on 19 December than on 9 December 2006.

A large algal bloom that was observed during sampling on 9 January 2007 was reflected in high concentrations of *Microcystis wesenbergii* (Table 7), which is also largely responsible for the peak observed in Figure 19.

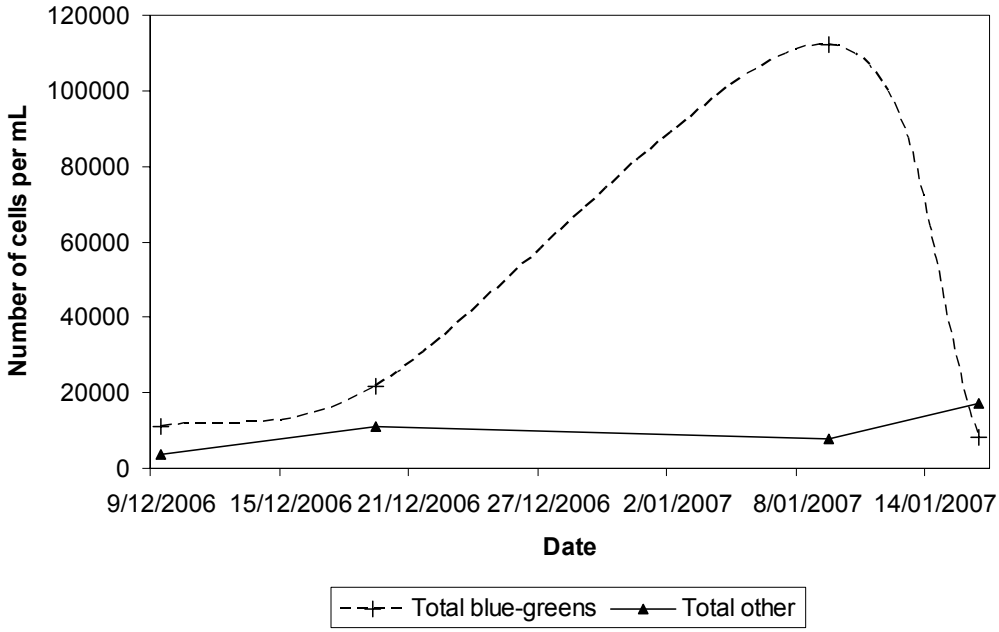

Figure 19: Phytoplankton cell concentrations separated into cyanobacteria and other species. Samples were collected on 9 and 19 of December 2006 and 9 and 16 of January 2007.

The Pediastrum and Trachelomonas species were present in higher than usual numbers on the 16 of January 2007, corresponding with a lower total number of blue-green cells than on other sampling days (Figure 19). The 16 of January 2007 was the only sampling day on which the total number of other cells exceeded the total number of blue-green cells.

4 Discussion

This study reinforces observations by Barnes (2002) that Lake Ngaroto is in a hypertrophic state. While water column concentrations of available nutrients (phosphate, ammonium and nitrate) are at relatively low levels, concentrations of total nutrients (TN and TP) and chlorophyll *a* are high, indicating that most nutrients are either maintained within a large water column organic component or, in the case of phosphorus, are also associated with inorganic sediment particles. Reinforcing the view that water quality is poor is the fact that the lake water is also dominated by cyanobacteria (blue-green algae) over summer, which are sometimes at very high concentrations. The cyanobacteria genera *Microcystis* and *Anabaena* that occur in Lake Ngaroto are known elsewhere to have toxin production potential, and high concentrations of *Anabaena* often impart tastes and odours to the water.

The Trophic Level Index (TLI) is a single numerical value that has been developed to provide a value for water quality in a lake (see Appendix B). It assigns equal weight to chlorophyll *a* concentration, total phosphorus and total nitrogen concentrations, and water clarity (Secchi depth) in deriving a value. The average TLI for Lake Ngaroto is 6.32, which compares with values of 4.7 for Lake Rotorua, 4.5 for Lake Rotoiti and 2.13 for Lake Taupo. The margin between the eutrophic Rotorua lakes (Rotorua and Rotoiti) and Lake Ngaroto is indicative that Lake Ngaroto is very degraded and very eutrophic ("hyper" or "super" trophic) yet, interestingly, Lake Ngaroto is still a very important asset for recreational activities (e.g. rowing, yachting and fishing).

As a result of the high phytoplankton biomass and suspended sediment concentrations, light penetration through the water column is poor. It is difficult to distinguish whether light or nutrients are limiting phytoplankton production in Lake Ngaroto, but it is probable that there is some combination of the two; nutrients will be recycled through the bioavailable phase only briefly under conditions in which the high phytoplankton biomass is both nutrient-limited and also light-limited. Even in hypertrophic systems, nutrient levels and recycling rates clearly play an important role in phytoplankton biomass and production, even when light climate is poor, and it is

for this reason that few if any shallow Waikato lakes can be regarded as being 'saturated' in nutrients.

Considering that the mean water depth in Lake Ngaroto is approximately 2 m, phytoplankton will be in the euphotic zone for just over 30 % of the time when the water column is well mixed, based on the high mean light attenuation coefficient (i.e. high turbidity) of around 7 m^{-1}. Phytoplankton species that have adaptations to enhance light capture will be selectively advantaged in this environment. Some diatom species, for example, can attain optimal levels of productivity at very low light intensities, but these silicified species generally have high rates of sedimentation and will be strongly disadvantaged by periods of stratification. In Lake Ngaroto the water column was stratified for at least 50 % of the time in January and this condition will lead to high rates of loss of negatively buoyant species from the water column. By contrast, positively buoyant (e.g. many species of cyanobacteria) or motile species (i.e. flagellates) will benefit from periods of stratification when they can adjust their position in the water column to optimise light capture. Cyanonbacteria are generally undesirable and blooms can be expected to occur under conditions of low wind and high integrated biomass through the water column. It is notable that there were increasing chlorophyll *a* concentrations and fluorescence values in January, as well as a marked peak in cyanobacteria cell concentrations The major bloom of cyanobacteria on 16 January occurred when the water column was relatively strongly stratified. In addition, concentrations of chlorophyll *a* also tended to be higher in the southern end of the lake, which may reflect the prevailing wind at the time of sampling, particularly in aggregating buoyant cyanobacteria to one end of the lake.

Another factor that indicates that Lake Ngaroto is in a degraded state is the depression of dissolved oxygen in bottom waters, even under relatively small measured vertical gradients of temperature. This loss of oxygen suggests that there is an abundant pool of organic matter in the bottom sediments of the lake, with additional losses of oxygen resulting from respiratory processes acting in the absence of photosynthesis in these deeper waters. It is possible that with stratification events of 2 to 3 days (e.g. mid-January) the bottom waters may even become anoxic, enhancing the release of nutrients from the bottom sediments and possibly bringing about releases of dissolved

phosphorus from an abundant supply of suspended sediments in the lower water column.

Lake Ngaroto has high levels of particulate organic and inorganic material that collectively reduces penetration of light to the low levels discussed above. Taking a specific light attenuation coefficient for phytoplankton of 0.02 m^2 (mg Chl *a*)$^{-1}$ and an average chlorophyll *a* concentration of c. 50 mg m^{-3} yields a partial attenuation coefficient for phytoplankton of approximately 1 m^{-1}. It is therefore evident that fine inorganic suspended sediment, measured in this study at concentrations up to 120 mg L^{-1}, is responsible for the majority of light attenuation in Lake Ngaroto, even accounting for a modest amount of light attenuation by non-algal particulate and dissolved organic material. It is likely that the high levels of suspended sediment largely enter the water column through wind resuspension of bottom sediments, perhaps with additional contributions from benthivorous fish, and that sediment disturbance is playing a key role in the elevated levels of particulate nutrients.

Concentrations of chlorophyll *a* and nutrients in the outflow provide a reasonable indication of levels in the surface waters of the lake itself. The outflow site may be a useful site for recording short-term variability with remote in situ sensors (e.g. chlorophyll fluorescence, temperature, dissolved oxygen and water levels). In addition, consideration could be given to deployment of an oxygen sensor in the lower levels of the water column in order to provide a continuous record of oxygen levels and gain more information about the extent of oxygen depletion in the lake.

It is evident that inflows to Lake Ngaroto are heavily laden with nutrients and suspended sediment. Of particular concern is the dominant discharge to the lake, MI3, which has extremely high levels of both total phosphorus (c. 0.3 mg L^{-1}) and total nitrogen (c. 2 mg L^{-1}), and also has high levels of dissolved (bioavailable) nutrient species. Without addressing these levels of contamination, and given the likely high rates of recycling of nutrients between the bottom sediments and water column of the lake, there will only be limited scope to improve water quality of Lake Ngaroto. Based on differences in concentration of inflow MI3 and the water column, not more than 30 % of nutrients entering the lake are likely to be retained within the lake sediment; by contrast relatively ‘stable’ lakes may have retention rates > 65 %.

A more definitive picture of nutrient and water loads to the lake should be possible with ongoing sampling that is planned through to June 2007 when the lake catchment begins to become saturated and a large number of tributaries begin to flow continuously.

This project will culminate in the development of a lake water quality model that will also have input data on nutrients and water yields predicted for the catchment. This model is expected to provide additional information on opportunities for managing water quality in the lake, including the effect of reducing nutrients in inflows and managing lake water levels. However, it appears that restoration of water quality of Lake Ngaroto will be an ongoing challenge that will necessitate a combination of techniques involving land use change, best-practice techniques for retention of soil and nutrients on land, managing riparian areas around streams and drains, and considering innovative techniques to attempt to control sediment resuspension within the lake.

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Appendix A

Appendix A, Figure 1: (A) Stock grazing at main inflow, (B) bank collapse into a drain, (C) soil erosion at drain, (D) dry drain covered with pasture, (E) inflow 12 showing bloom of *Microcystis wesenbergii* and (F) drain flowing into a wetland before entering the lake. Note: Arrows indicate flow direction towards the lake.

Appendix B

Note on Trophic Level Index

Introduction

Trophic state indices are commonly used to make assessments about the productivity of a waterbody. No single indicator provides an exact quantitative assessment of trophic state because there are many interacting factors (e.g. mixing depth, grazing, temperature etc.) that influence productivity. Composite measures related to nutrients (e.g., total phosphorus, TP) or light (e.g., Secchi disk depth, SD) provide chemical or physical indicators, respectively, with which to assess trophic state, whilst biomass (e.g. chlorophyll *a*, Chl*a*) provides a more direct indicator of water column primary production. Chlorophyll *a* is relatively simple to measure and explain, and most relevant to the concept of productivity. The three indices (TP, SD and Chl*a*) are most commonly based on near-surface concentrations and may be averaged spatially (e.g. across stations) or temporally (e.g. over seasons or years) to smooth some of the inherent natural variations in each index. Trophic state indicators should not necessarily be equated to water quality, however, which tends to be a more subjective judgment often influenced by water use (see Vant and Davies-Colley, 1988).

There has been a tendency to average up to three or four of the trophic state indicators at a given point in time rather than to prioritise only one indicator or make comparisons between indicators. A single value is convenient in that it may be more readily interpreted and compared by non-specialists. On the other hand, the averaging process allocates all contributing indices equal weight, which Carlson (1983) argues strongly against.

The two trophic state indices that I consider here are the Trophic State Index (TSI: Carlson, 1977) and the Trophic Level Index (TLI: Burns et al., 2000). The TSI allocates values to SD, TP and Chl*a* that generally fall in the range 0 to 100, though values can theoretically exceed 100. The average of these values is used to provide an overall TSI value. The Trophic Level Index (TLI) assesses trophic state with the same three parameters but also includes total nitrogen (TN). The TLI was adopted for the New Zealand Lakes Water Quality Monitoring Programme, and has subsequently

been recommended by the Ministry for the Environment (Burns et al., 2000).Individual values of the TLI can also be averaged to provide an overall TLI value. Table 1 compares the equations used in the TSI and TLI calculations.

Other variables to increase predictive power of the average TSI value have been added in a number of studies, including macrophyte biomass, to reflect partitioning of productivity between phytoplankton and macrophytes, which may be particularly important in lakes with relatively large littoral areas (Canfield et al., 1983). In monomictic lakes, hypolimnetic oxygen depletion has in many studies been closely related to primary production (e.g. Schallenberg and Burns, 1999). It provides a useful indicator of trophic state in the Rotorua lakes (Hamilton, 2003), and its recent adoption in annual reporting of the Rotorua lakes water quality (Scholes, 2004) is a useful addition to trophic state assessments previously based only on the TLI. The use of the oxygen depletion rate can be used to increase confidence in inter-annual comparisons which may have limited data sets, as other measurements such as Chl*a*, TP and TN tend to be more variable in discrete samples. The use of TN in the TLI (TLI(TN)) is another example of an attempt to increase predictive power by use of an additional variable and also reflects the origins of the index development, i.e., in New Zealand (Table 2, Burns et al., 2000). Phytoplankton communities in New Zealand tend to differ from those of commonly described in north temperate lakes, in that they are often N-limited (White 1983; White et al. 1985).

TLI values that include both TN and TP (TLI(TP)) effectively produce an increase in the weight allocated to chemical (nutrient) predictive powers. TN and TP can generally be expected to be closely correlated (Vollenweider and Kerekes, 1982) and therefore so will their TLI values. However, when one nutrient is strongly limiting and one is well in excess of phytoplankton growth requirements, the average TLI value may be slightly inflated. Environment BOP could therefore compare the current TLI methodology with one that uses an average based only the lower of the TLI values for TN and TP. If it was thought that this approach was useful, TLI values could be re-calculated through all historical data sets to ensure no bias with the slight change in methodology. There could, however, still be caveats placed on the new methodology: take for example the case of a eutrophic N-limited lake where N-fixing cyanobacteria are dominant; the TLI(TN) value might be artificially low, especially in

comparison to the TLI(Chl*a*) value. Such a caveat says simply that knowledge of the system in question is a critical adjunct to the application of any index.

The recommendation above is not likely to change to any degree the application of the TLI in the Environment Bay of Plenty Land and Water Plan. It may mean a slight refinement of the TLI calculation technique or values through time; part of a natural process to adopt best scientific practices as they become available. If a slightly different approach to determining the TLI was adopted, for example, then there is always an option to compare the existing TLI value with new one using existing data sets, so that the effect of such a change, though likely to be small, can be quantified.

In the application of the TLI, Environment BOP will need to be mindful of 'lag effects' due to the long response time for underlying groundwater to reflect land use change, and the dominance of groundwater as a component of streamflows in catchments of the Rotorua lakes. Thus the effects of land use change on the TLI value of a lake may potentially take many years to approach equilibrium, and reaching TLI 'targets' may be delayed. Similarly, most areal nutrient yields calculated for different land uses represent an equilibrium case in which the yield has already equilibrated to the land use under consideration. The work that Environment BOP has commissioned by the Institute of Geological and Nuclear Sciences to 'age' groundwater, may need to be built into nutrient budget calculations and ultimately into the TLI, because managing nitrogen inputs to lakes with potentially a very large residual store of groundwater nitrogen may be very difficult, i.e., the TLI may get worse before it improves to reflect the benefits of land use change to lower nutrient yields.

In summary, no trophic level indicator is perfect because of the many complexities and interacting factors that control trophic state, but the TSI has effectively stood the test of time and is still in very common use today for trophic state assessments of Northern Hemisphere temperate lakes. This reflects the fact that TSI predictions often fall within error limits of measurements and that input variables are generally collected and archived as a component of most lake monitoring programmes. The TLI can be interpreted similarly; it will also provide a good indicator of trophic state for New Zealand lakes, no matter that there is greater emphasis on chemical measurements compared with the TSI. The TLI will be useful – taking heed of

comments above about limiting nutrients – for determining whether trophic state of a lake is changing through time and for making rough assessments of trophic state variations between lakes. Burns et al. (2000) provide criteria, based on level of significance ('p-value'), for estimating whether trophic status of a lake is truly changing through time, but these p-values should be adapted and refined as data inventories are built up, and should not be considered to be fixed.

The main difficulty with any of the trophic state indices may arise when they are used outside of their intended bounds, i.e., in a predictive mode without very detailed considerations of how a system might respond. The apparent redundancy of TLI(TN) or TLI(TP) in the TLI makes this more likely to occur than for the TSI, i.e., reducing either TN or TP when the other nutrient is strongly limiting may have beneficial effects on the calculated average TLI, but could have relatively little effect on the actual trophic state. For this reason, the objective of Environment BOP to return lakes to former TLI values based not only the average TLI but also the components (TLI(TP), TLI(TN) and TLI(SD)) is a sound approach, though in reality it may be difficult to steer a lake a tightly defined recovery path, particularly when there is commonly a strong hysteresis in the recovery (Harris, 1999), and in an environment where there is a strong trend of increasing nitrate in stream inflows that are driven mostly by progressive changes in groundwater composition that reflects pastoral conversions (Rutherford et al., 2003).

Appendix 2, Table 1. Comparison of Trophic State Index and Trophic Level Index

Variable	TSI Equation	TLI Equation
Secchi disk depth (m)	TSI(SD) = 60 - 14.41 ln(SD)	TLI(SD) = 5.10 + 2.27log(1/SD – 1/40)
Chlorophyll *a* (μg L^{-1})	TSI(Chl*a*) = 9.81 ln(Chl*a*) + 30.6	TLI(Chl*a*) = 2.22 + 2.54log(Chla)
Total phosphorus (μg L^{-1})	TSI(TP) = 10(6-(ln(48/TP)/ln2))	TLI(TP) = 0.218 + 2.92log(TP)
Total nitrogen (mg L^{-1})	TSI(TP) = 14.42 ln(TP) + 4.15	TLI(TN) = -3.61 + 3.01log (TN)
All variables (all in mg L^{-1})		TLI = (TLn + TLp + TLs + TLc)/4

Appendix 2, Table 2. Values of variables defining the boundaries of different trophic levels (Burns et al., 2000).

Nutrient enrichment category	Trophic state	Trophic level	Chla (mg/m^3)	Secchi depth (m)	TP (mg/m^3)	TN (mg/m^3)
Low	Oligotrophic	2.0 to 3.0	< 2	> 7.0	< 10	< 200
Medium	Mesotrophic	3.0 to 4.0	2 – 5	3.0 - 7.0	10 – 20	200 – 300
High	Eutrophic	4.0 to 5.0	5 – 15	1.0 – 3.0	20 – 50	300 – 500
Very high	Supertrophic	5.0 to 6.0	15-30	0.5 – 1.0	50 – 100	500 – 1500
Extremely high	Hypertrophic	6.0 to 7.0	> 30	< 0.5	> 100	> 1500

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