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Lake Ototoa: a limnological assessment of recent condition and trends

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Lake Ototoa: a limnological assessment of recent condition and trends

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1 Executive Summary

Lake Ototoa, on the South Kaipara Head, has one of the highest water qualities of all the lakes within the Auckland area but there are indications that its water quality is declining. However, because of inconsistencies between some reported indicators over different time-scales, Auckland Regional Council (ARC) asked NIWA to conduct a limnological assessment of the water quality of the lake to determine its recent condition. This report presents an evaluation of Lake Ototoa water quality with reference to the recent reports, based on the results of a detailed water quality survey during 2005-06 compared with data from the current ARC lakes monitoring programme from 1988 to 2006 as well as historical data from the literature. This report includes an evaluation of the role of in-lake processes and an estimate of external inputs. Flux rates were estimated and are presented to assist the ongoing development of a predictive model of the lake.

There are lines of conflicting opinions on water quality:

1. Evidence of the high water quality of this lake are the very low nutrient concentrations and algal biomass in the water column, and the development of a deep chlorophyll *a* maximum at the thermocline during summer stratification. A recent survey of the submerged vegetation of the lake using the Lake Submerged Plant Indicators (LakeSPI) showed the lake was in good condition and "*did not show any change in lake condition compared to 17 years previously*." (de Winton et al. 2005)

2. Evidence for the "trend" of decline in water quality of Lake Ototoa center around reported changes in the water quality indicators, percent annual change (PAC) and the trophic level index (TLI) (Barnes & Burns 2005). They found that "*the average PAC determined from the four key variables*" (chlorophyll *a*, Secchi depth, total nitrogen, and total phosphorus) "*indicated a significant decline in water quality between 1992 and 2005, with all four deteriorating*".

In this study, the limnological evaluation of the lake found that nutrient concentrations in the lake were generally low as were the nutrient concentrations in the stream and groundwater inflows. With TN:TP > 10:1, the lake was strongly P-limited for algal growth. External sources provided the majority of the TN and TP to the lake water column with a large Aeolian component. Internal cycling of nutrients from the sediments was the major source of dissolved inorganic nitrogen and phosphorus. Aeolian inputs coupled with wind-induced stirring and resuspension of littoral sediments contributed to the highly variable water clarity and reduction in water clarity in the long term. However, while there was some correspondence of water clarity with climate through the El Niño Southern Oscillation (ENSI) index since 1999, there was a significant positive correlation of water clarity with local rainfall since 1994 ($p < 0.001$, $r^2 = 0.87$, $n = 10$) which suggests a "damping down" of dust and dirt that could be blown into the lake rather than this material being carried into the lake in rainfall runoff.

In this study, clear evidence was found in the long term data of a "step-wise" decline in water quality. Primary evidence was a 33% decrease in water clarity between 1970

and 1988 but no change in the mean monthly water clarity between 1988 and 2006. The second set of evidence was a change in the hypolimnetic oxygen depletion rate between 1970, when it was 38 mg m^{-3} d^{-1}, and 2006 when the rate had increased to about 200 mg m^{-3} d^{-1}. In 1969/70 the minimum oxygen concentration in the hypolimnion was 2.3 g m^{-3} but in 2005/06 the hypolimnion became anoxic. Inadequacies in the ARC lakes monitoring data before 1999 prevented determining whether this was a step-wise change of a more gradual trend in the data. Similarly, although weak trends of increasing total nitrogen (TN) and total phosphorus (TP) concentrations between 1990 and 2006 were also found, these were at levels of <10% of the analytical precision in the ARC lakes monitoring data.

While there has been a change in water quality since 1970, the indications are that change has been driven by external events including changes in land use associated with forestry on the western side of the lake. The last major event occurred in 1997/8 following the harvesting of a compartment of pine forest on the shores of the lake. The subsequent slow recovery from that event may be exacerbated by continued forestry harvesting that allows a high Aeolian input to the lake in the present El Niño weather patterns. These have predominantly westerly winds across the forest to the lake.

Conversely, voluntary changes by farmers in land use practices in the lake catchment may have enhanced the recovery of the lake water quality since the 1997/98 event despite the continued forest harvesting.

This study has highlighted the role of Aeolian inputs to the lake from within and outside the catchment. It has also highlighted the lack of knowledge about the effects of the pine forest on this lake. Sediment cores should provide evidence of the link between land use and the water quality in the lake.

2 Introduction

Lake Ototoa has one of the highest water qualities of all the lakes within the Auckland area. Indications that the water quality has declined (e.g., Barnes & Burns 2005) have prompted calls for urgent attention to save Lake Ototoa (Auckland Regional Council (ARC) web site articles). However, there are inconsistencies between some indicators as to the extent of any decline in water quality, whether any decline is a trend or an event-driven change, and whether any change was recent or long-term. ARC asked NIWA to resolve this issue by conducting a detailed limnological assessment of the lake to evaluate changes in water quality based on data collected for this study, data from the current ARC monitoring programme and historical data.

The conclusion that the water quality of Lake Ototoa has declined was drawn from changes in the water quality indicators, percent annual change (PAC) and the trophic level index (TLI) (Barnes & Burns 2005). They found that "*the average PAC determined from the four key variables*" (chlorophyll *a*, Secchi depth, total nitrogen, and total phosphorus) "*indicated a significant decline in water quality between 1992 and 2005, with all four deteriorating*". They also concluded that "*the decline in water clarity appeared to be driven by an increase in phytoplankton abundance due to increasing levels of inorganic nitrogen*". They went on to say that "*the lack of analytical precision in dissolved reactive phosphorus measurements prevented detection of any trend in inorganic phosphorus, although total phosphorus had increased by 0.60 mg.m^{-3}/yr ($p<0.01$) over the observed period*".

Barnes & Burns (2005) noted an apparent cyclical pattern in the time-series data, especially the water clarity data, "*which showed a high – low – high oscillation between 1992 and 2005 and when plotted with the El Niño Southern Oscillation phenomenon (ESO) exhibited evident correspondence between 1999 and 2002 … The low water clarity period observed between 1998 to 2002 appeared to coincide initially with a strong El Niño event and continued through subsequent La Niña years until recovering from 2002 onwards. This suggests observed changes to Lake Ototoa water quality may haven been cyclic, climate driven behaviour rather than a typical linear trend.*"

The cyclical nature of changes in water quality in Lake Ototoa were also noted by Duggan & Barnes (2005) who found that the inferred trophic state of the lake was similar at the beginning and end of a 2-year study but there was a consistent pattern of change over time that may correspond with weather patterns. In contrast to the changes in water quality indicated in the Barnes & Burns (2005) report, the apparent lack of change in water quality indicated by the Duggan & Barnes (2005) study was supported by results of a survey of the submerged vegetation of the lake using the Lake Submerged Plant Indicators (LakeSPI) method (de Winton et al. 2005). That study showed the lake was in good condition and "*did not show any change in lake condition compared to 17 years previously.*"

This report presents the results of a detailed limnological assessment of the lake and the use of these data together with the current ARC monitoring programme and historical data to evaluate changes in lake water quality. The data assessment includes evaluation of the role of in-lake processes for the supply of nutrients for water column production. The study also provides flux data to assist the ongoing development of a predictive model of the lake.

3 Methods

3.1 Site

Lake Ototoa (Fig. 1), an elongated dune lake situated at the northern end of the South Kaipara Head [36° 31'S, 174° 14'E], is the largest (surface area 1.6 km^2), deepest (29 m), and cleanest of a sequence of ARC-monitored dune lakes on the west coast of the North Island between Manukau Harbour to the south and Kaipara Harbour to the north. (See Appendix 1 for hypsographic data). The lake has a catchment area of about 5.1 km^2 almost equally divided between native forest/scrub (34%), exotic pine forest (27%) and pasture (39%) (Barnes & Burns 2005). The lake lies between steep pastured hills on the eastern side and pine tree plantations on the sand dunes on the western side, with the native forest and scrub covering the steep western shores and the stream channel at the northern end of the lake. The lake orientation and position in a narrow valley tends to direct the south-westerly – north-easterly wind flows along the axis of the lake. The lake has one small stream inflow (about 15 L s^{-1}) plus several ephemeral streams but there is no surface outlet. The location of the stream inflow at the head of a long narrow sidearm (Fig. 1) suggests that the stream water is unlikely to have a direct impact on the main body of the lake. Although there is no data on groundwater, it is likely that there are areas of groundwater inflow through the sand into the lake and possibly a groundwater discharge from the lake. The lake has an almost continuous buffer zone of marginal vegetation between the stream and any groundwater and the open waters of the lake.

Originally surrounded by sand dunes and coastal native forest, the catchment was first developed into farmland which was fertilized with superphosphate by aerial top dressing (Green 1975). The native Kanuka forest on the western side of the lake was cleared and re-planted in exotic pine forest, including a small forest compartment which extended to the lake shore. This compartment was clearfelled in 1997/98 (Fig. 2). Before 2000, much of the pastured land was used for dairy farming . Land management practices changed around 2000 and the present land use on the eastern side is deer and Alpaca farming. Except for a small section of southern shore, the lake margin has been fenced to exclude direct stock access, although feral Fallow deer can roam the retired land, especially in the regenerating native forest around the stream inflow. A large house has recently been built near the lake below the original farm house. Water is drawn from the lake as a local area water supply.

Figure No. 1

Site map and bathymetry (Irwin 1973) of Lake Ototoa showing the various sampling sites (text and X) used in previous sampling studies relative to the present study (coloured symbols). The routine ARC monitoring site with instrument mooring is at LTB.

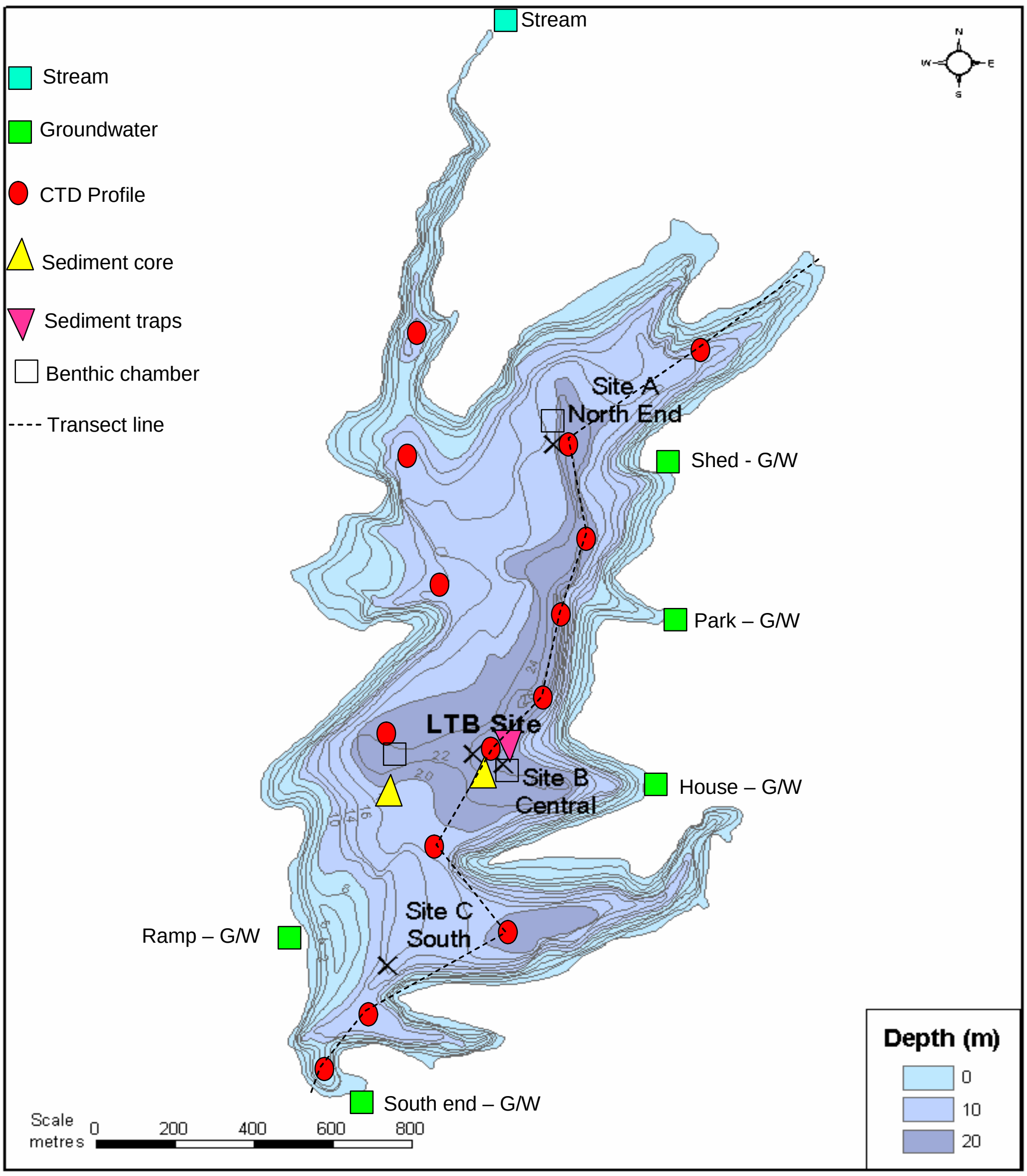
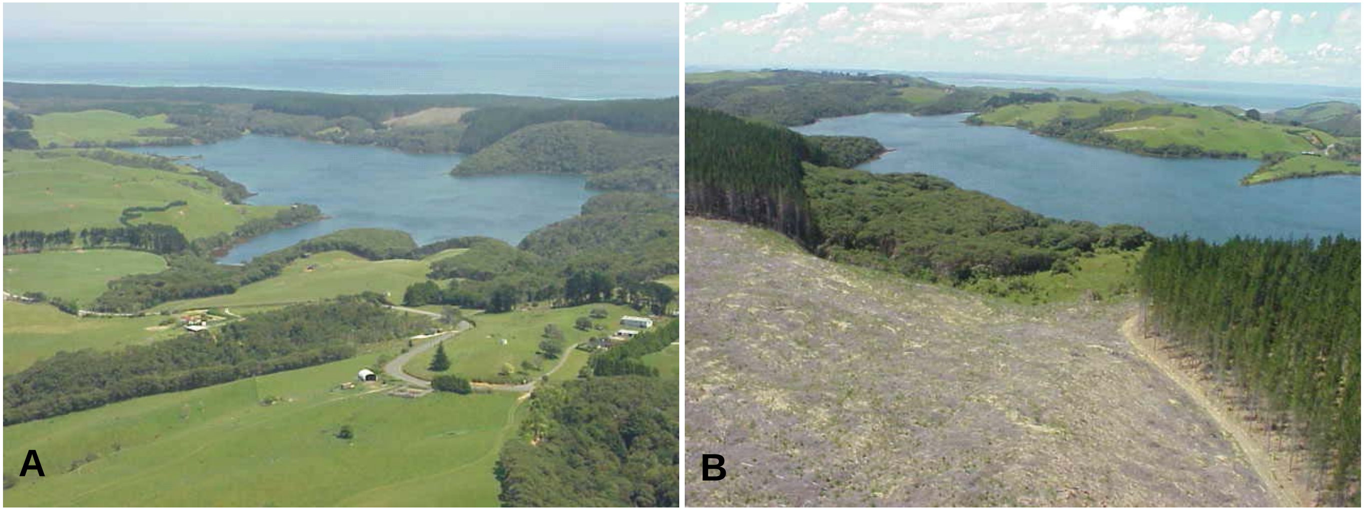


Figure No. 2

Areal photos of Lake Ototoa in November 1999 A) from the northern end looking southwest across the pine forest towards the Tasman sea; the pale patch on the western shore is recently clear-felled pine forest, B) from above the clearfelled pine forest on the western shores of the lake looking north-east across the farmland towards the Kaipara Harbour.



3.2 Background data

Published information on Lake Ototoa is sparse but extends over a long time period. The lake [incorrectly named as Lake Rototoa] was visited on 3-5 February 1950 (Cunningham et al. 1953) as part of a survey of dune lakes on the west coast of New Zealand (Summary of physico-chemical data is included in Appendix 1). The bathymetry of the lake (Fig. 1) was mapped in 1970 (Irwin 1973). An intensive study of the lake's physico-chemical features and plankton was made with almost weekly visits from March 1969 to March 1970 (Green 1973, 1975, 1976). (A summary of this data is included in Appendix 1.)

Subsequently, the water quality of the lake has been monitored by ARC with seasonal sampling based on 4 visits per year since February 1988. Evaluation of that data up to 1999 (Gibbs et al. 1999) determined a number of inadequacies in both sampling and analyses, which have since been corrected.

The ARC monitoring programme is on-going and has recently been increased to 6 visits per year with additional installations of in-lake monitoring instruments (temperature and dissolved oxygen) and a weather station on a hill on the eastern side of the lake. The ARC monitoring programme was augmented with a more intensive temperature and oxygen profiling programme during spring and summer in 2002/03 to assess the rate of bottom water (hypolimnetic) oxygen depletion as an indicator of the water quality status of the lake (Hawes & Haskew 2003, 2004). The present study also augments the ARC monitoring programme by examining aspects of the in-lake processes including the fluxes of nutrients in and out of the sediments to determine the magnitude of the internal nutrient loads.

3.3 Sampling

This study comprised 4 visits to the lake by NIWA to augment a ARC monthly water quality sampling programme. Sampling dates were 5-6 December 2005, and12-13 January, 19-20 March and 20-21 June 2006. On each visit, the lake physical parameters where measured with an *in situ* recording conductivity-temperature-depth (CTD) profiler [RBR XR420f] fitted with a dissolved oxygen and chlorophyll fluorescence sensor. Profiling sites are marked on the site map (Fig. 1). Water clarity was measured with a quartered black-and-white 20-cm diameter Secchi disc.

Sediment traps were installed in the lake near the routine ARC mid lake sampling site (Fig. 1) on each sampling occasion to determine sedimentation rates. The traps consisted of two sets of 3-cup trap tubes (65mm ID, 500 mm long with a funnel and drain tap inserted at the bottom) attached to a mooring line at 8m and 21m below the surface in 22m water depth. The mooring line was held taught between a 10 kg anchor and a sub-surface 200mm hard buoy 3-m below the surface. The traps were retrieved after 24 hours and the trapped material measured for suspended solids (SS) and particulate carbon, nitrogen, and phosphorus (PC, PN, and PP). The composition of the trapped material was also examined microscopically

Nutrient fluxes from the sediments were assessed using benthic chambers [0.5m x 0.5m square, volume 24 litres] lowered to the lake bed and sampled at timed intervals via a 3-mm ID hard nylon tube to the surface. Benthic chambers were deployed near the mid lake site (19 m) and at the northern end of the lake (20 m) in December 2005 and at the mid lake site (20 m) and on the western side of the central basin (11 m) in January 2006 (Fig.1). Waters samples collected were analysed at the NIWA laboratory for dissolved reactive phosphorus (DRP), nitrate plus nitrite nitrogen (NO_3-N), and ammoniacal nitrogen (NH_4-N). Dissolved inorganic nitrogen (DIN) is the sum of NO_3-N plus NH_4-N concentrations. Dissolved oxygen concentrations inside and outside the benthic chamber were measured with in situ recording optical oxygen sensors (Eijkelkamp OTD-Diver). Time-series near-bottom oxygen concentrations were measured using a set of 4 OTD-Divers at 0.5m intervals above the lake bed at the depth of thermal stratification on one occasion.

Sediment cores were taken, using a Jenkin's Corer, from the lake bed above and below the depth of the thermocline to assess pore-water concentrations of DRP, NO_3-N and NH_4-N in the top 20mm. An Ekman dredge (sender-operated box corer) was also used to collect bulk sediment samples.

Lake water samples were collected from depths of 3, 8, 12, 15, and 21m below the surface at the mid lake site near the sediment traps so that the trap data could be corrected for ambient SS concentrations. The water samples were analysed at the NIWA laboratory for chlorophyll *a*, SS, DRP, total dissolved phosphorus (TDP), particulate phosphorus (PP), total dissolved nitrogen (TDN), PN, and PC. An inter-laboratory comparison of analytical results from the lake water samples was made on 12 January 2006 between the NIWA laboratory and Watercare Services Ltd (WSL) laboratory (Appendix 2).

Stream inflow and groundwater samples were collected at 5 locations (Fig. 1) using a NIWA sampling penetrometer (John et al. 1977) on each sampling visit. These water samples were analysed for DRP, TDP, NO_3-N, NH_4-N, and TDN and the stream water was also analysed for TN and TP.

The data collected during these visits was combined with the ARC monitoring data to provide the data for the development of a hydrodynamic model of the lake using "DYRESM" to determine how the physical structure of the lake is likely to have responded over time to climatic variability. This modelling will be reported separately.

4 Results

The results are reported for the 4 visits to the lake in this section and briefly discussed in relation to the ARC monitoring and historic data. More detailed discussion and evaluation of specific aspects are continued in the appendices as noted.

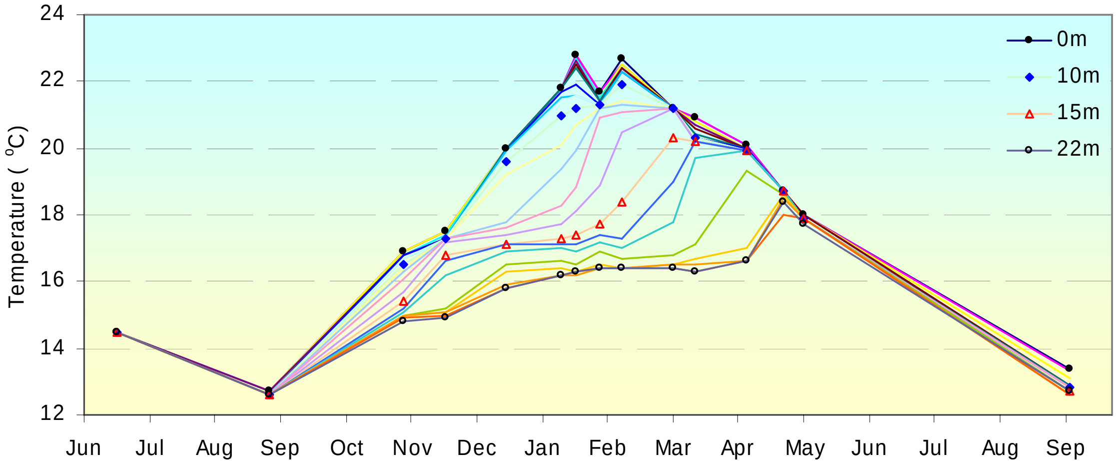
4.1 Physical structure

4.1.1 Temperature

ARC monitoring data show that Lake Ototoa thermally stratifies each year beginning in Spring (September/October) and finishing in Autumn (April/May) (e.g., 2002-2003, Fig. 3). Although the temperature gradient is >2°C and up to 7°C, the hypolimnion continues to warm by about 3°C over the early stratified period. This implies that the lake experiences mixing events which penetrate the thermocline.

Figure No. 3

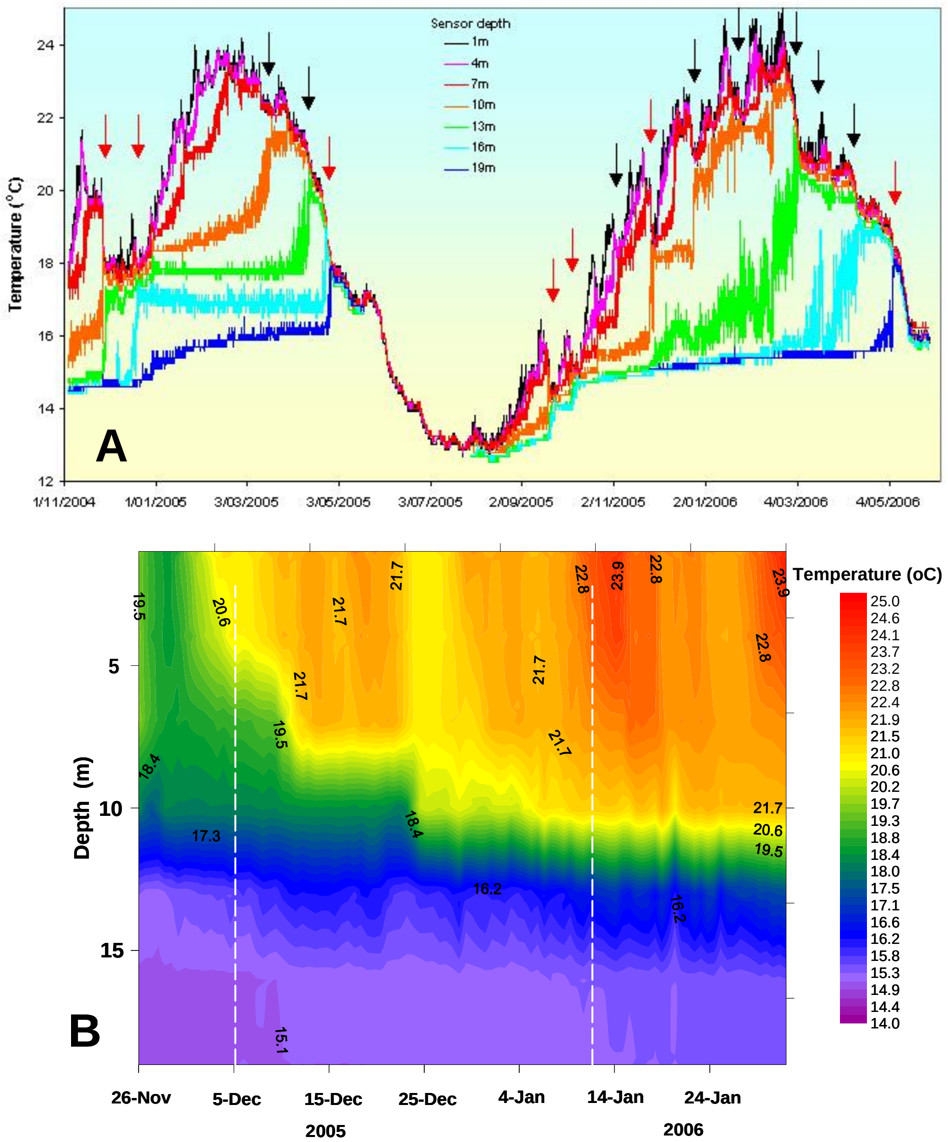
Temperature structure of Lake Ototoa (ARC data 2002-2003) showing the onset of thermal stratification in Spring (September/October) and lake mixing in Autumn (April/May). Temperature lines at 1-m intervals with specified depths marked with symbols.



Examples of deep mixing can be seen in the high resolution (hourly) temperature data from the ARC thermistor chain (Fig. 4A). Vertical arrows indicate wind-induced mixing events which mixed the water column to at least 10 m, with red arrows marking events that mixed through the thermocline. An example of turbulence at the thermocline can be seen in the contour plot of the thermistor chain data from 26 November 2005 to 1 February 2006 (Fig. 4B). This period covers the 5 December 2005 and 12 January 2006 sampling visits to the lake. The weather had been relatively calm before the 5 December visit and there appeared to be minimal vertical movement on the thermocline. In contrast, strong winds before the 12 January visit had set the thermocline in motion with vertical movements of up to 0.5 m but possibly exceeding 1 to 2 m at the time of the wind event. Oscillations at a frequency of <1 hour were not detected by the sampling time interval of the thermistor chain.

Figure No. 4

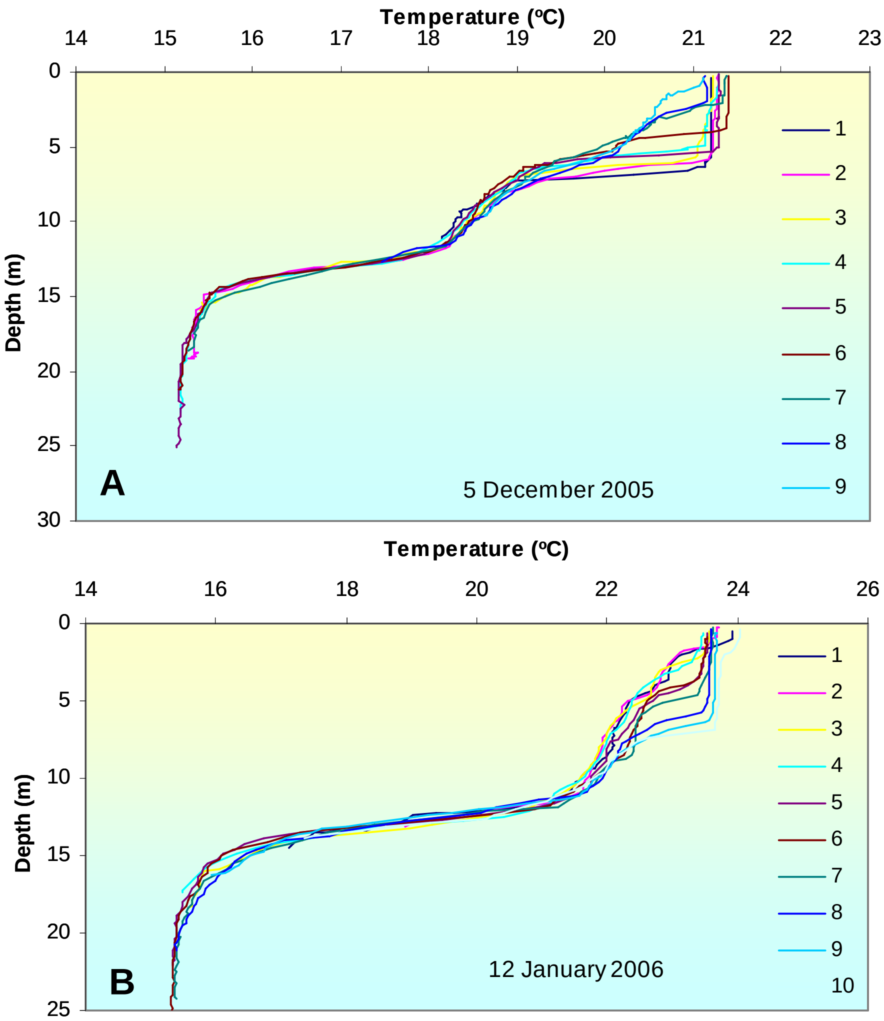
Temperature structure of Lake Ototoa from fixed-depth temperature sensors (thermistor chain) deployed at the monitoring site. Data were recorded at hourly intervals. A) Red arrows indicate mixing events that penetrated the thermocline, black arrows indicate mixing events reaching at least 10 m depth; B) Contoured thermistor chain data across the sampling periods 5 November 2005 and 12 January 2006 (white broken lines), showing vertical movement of the thermocline associated with wind-induced stirring.



Temperature profile data on 5 December 2005 showed that the thermal structure of the lake was complex with a double thermocline, the first at around 6 m and the second at around 13-15m (Fig. 5). This double thermocline was also present in the 12 January and 20 March profile data indicating that it was a feature of the lake rather than an unusual one-off observation. This feature was also noted by (Green 1975).

Figure No. 5

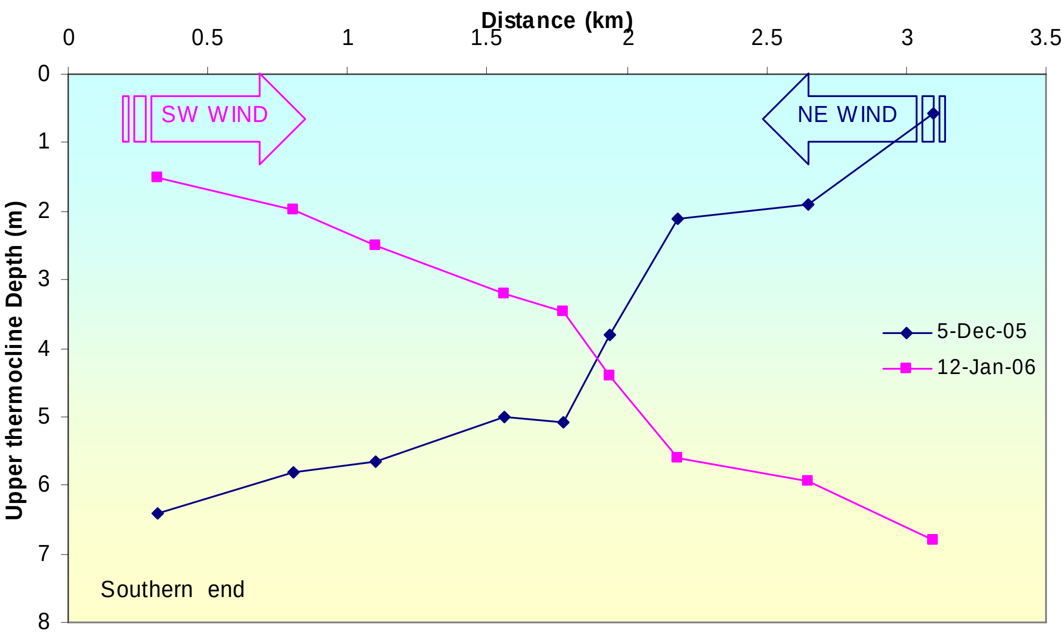
Temperature profiles in Lake Ototoa on A) 5 December 2005 and B) 12 January 2006 showing the presence of double thermoclines and the tilting of the upper thermocline. Coloured lines refer to the profiling position along the main axis (Fig. 1 broken line) with 1 at the south end of the lake



Closer examination of the upper thermocline on 5 December 2005 showed that it was tilted against the wind. The wind was a steady breeze from the north which appeared to have pushed the warm surface water down at the south end of the lake and caused the upper thermocline to reach the surface of the lake at the northern end (Fig. 6). On 12 January 2006 the wind was stronger from the south and the upper thermocline had tilted in the opposite direction, deepening at the northern end and reaching the surface at the southern end of the lake (Fig. 6).

Figure No. 6

Depth to the top of the upper thermocline in Lake Ototoa on 5 December 2005 and 12 January 2006 relative the wind direction on each day. X-axis is profile site distance along the axis of the lake (Fig. 1) from the southern end.



These data confirm the thermistor chain data finding that wind affects the upper thermocline which acts as a "pump" to get warm oxygenated water deeper into the lake. The lower thermocline appeared to be unaffected by the wind events at the times of sampling, with the hypolimnion remaining isolated from the upper water column. However, the thermistor chain data show that there was mixing across the thermocline on occasion (Fig. 4A).

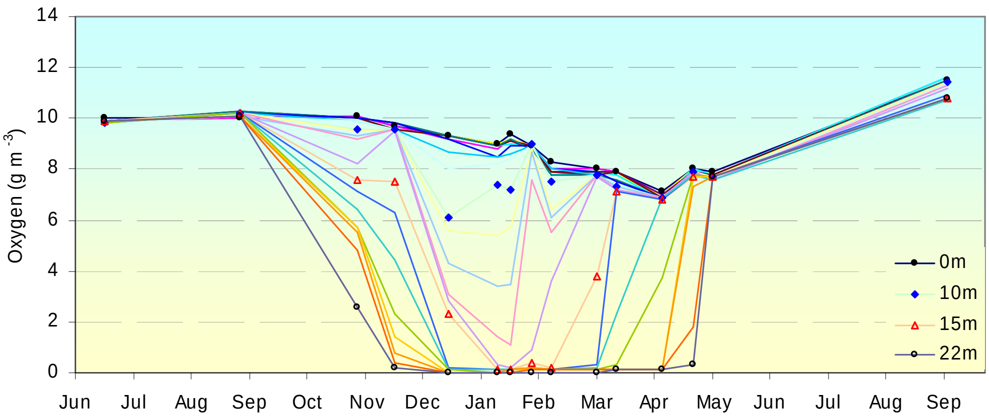
Presenting the profile data as contour plots of each transect (Appendix 3-Temperature) showed that from spring to autumn the thermal structure became stronger and the lower thermocline became thinner as the warm water moved deeper into the lake. The lake was fully mixed at the time of the 20 June 2006 sampling.

4.1.2 Oxygen

Once Lake Ototoa thermally stratifies, ARC monitoring data show that the hypolimnion rapidly loses oxygen with the bottom waters near the sediments becoming anoxic by November and the whole hypolimnion below 16 m becoming anoxic by December (e.g., 2002-03, Fig. 7). The hypolimnion remains anaerobic until the lake mixes in autumn.

Figure No. 7

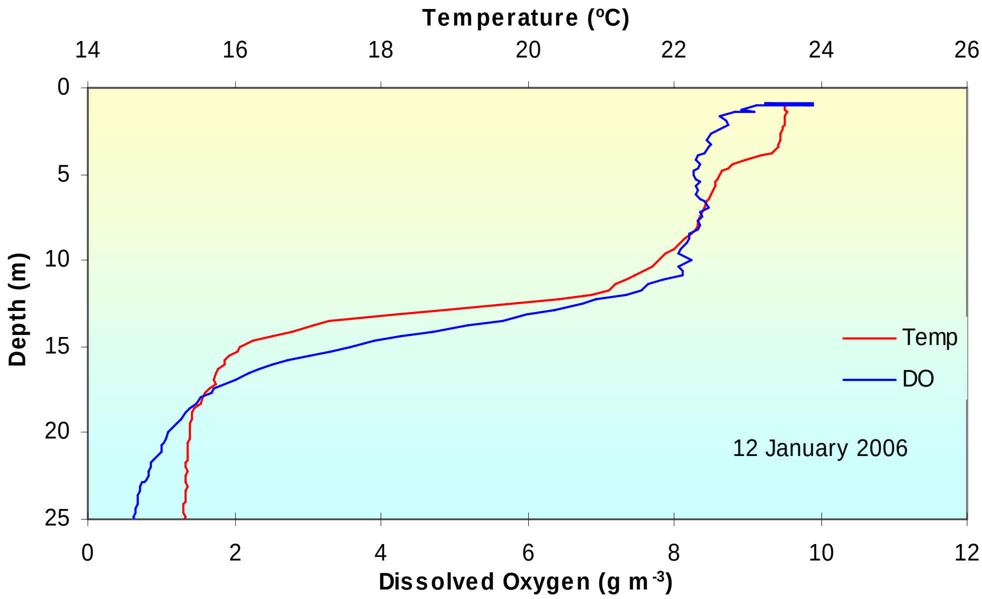
Oxygen concentrations in Lake Ototoa (ARC data 2002-2003) showing the rapid loss of oxygen from the bottom waters in spring (September/October) and lake mixing in autumn (April/May). Oxygen concentration lines at 1-m intervals with specified depths marked with symbols.



High resolution oxygen profile data from each of the sampling visits during this study showed that the loss of oxygen was below the deeper thermocline (e.g., 12 January 2006, Fig. 8), and became more tightly coupled with that boundary through the middle of summer, (see Appendix 4 –Oxygen for more details).

Figure No. 8

Oxygen concentrations in Lake Ototoa on 12 January 2006 compared with temperature structure.



These high resolution data indicated that there may be some degree of inter-annual variability in the severity of hypolimnetic anoxia with the January 2006 profile (Fig. 8) showing low levels of dissolved oxygen between 15 m and 20 m while the hypolimnion below 15 m appeared to be anoxic by January 2003 (Fig.7). In 1969/70, the minimum hypolimnetic oxygen concentration was 2.3 g m^{-3} (Green 1975).

The implications from these oxygen data (Figs. 7, 8) are that the hypolimnion was poorly mixed (i.e., there was an oxygen gradient through the hypolimnion), and that the sediments were not highly enriched with organic matter (i.e., the oxygen profile was not showing zero oxygen at the sediment surface at this site in January 2006).

The presence of low levels of oxygen in the hypolimnion in January 2006 was of interest given that the ARC *in situ* oxygen logger data at 20 m recorded zero oxygen in December 2005 (Fig. 9). It implies that oxygen was being mixed into the hypolimnion during the wind-induced mixing events such as those identified by the temperature data (Fig. 4). The event around 25 December 2005 was strong enough to mix through the thermocline and the oxygen measured in the hypolimnion on 12 January 2006 (Fig. 8) may have been the residual oxygen from that event.

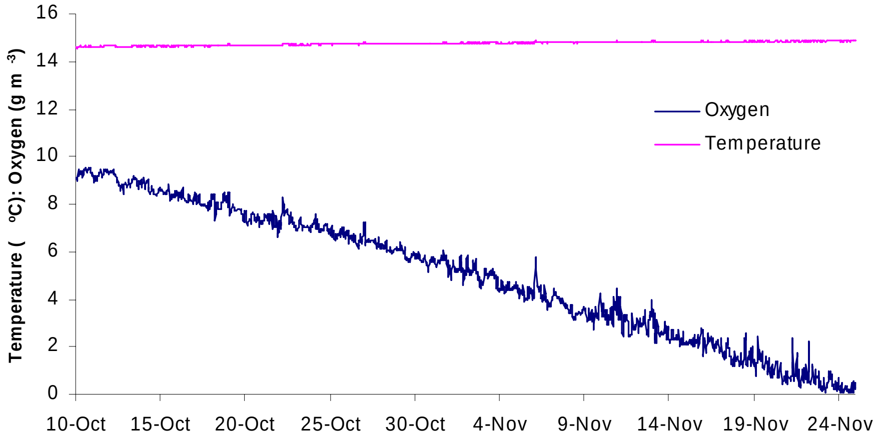
On a smaller scale than the deep mixing events, oscillations of the thermocline, seen as irregularities between 10 m and 13 m in the contoured temperature plot (Fig. 4B), indicate the presence of internal waves (seiches) on the deep thermocline. (See Appendix 4 Oxygen for more detail.)

The rate of oxygen depletion in the hypolimnion can be estimated from the time-series oxygen data collected from the ARC instrument system for the 20 m depth stratum (Fig. 9). The oxygen concentrations decreased from 100 % saturated to 0% saturated in 45 days while the temperature remained essentially constant indicating that there was no mixing event during that period. A linear regression through the oxygen data gave an estimated hypolimnetic oxygen depletion (HOD) rate of 205 mg m^{-3} d^{-1}. This was higher than, but comparable with, the HOD rate of 124 mg m^{-3} d^{-1} estimated by Hawes & Haskew (2003) for 2002. The 2002 estimate was based on just 3 data points and was calculated for the whole depth of the hypolimnion. In contrast, the 2005/06 estimate was based on a regression through several thousand data points but at just one depth (20m). Considering that there was still some oxygen in the upper hypolimnion while the water closer to the sediments became anoxic, it is likely that the true HOD rate lay somewhere between 124 and 205 mg m^{-3} d^{-1}.

These HOD rates were substantially higher than the estimate by Green (1975) for 1969/70 of about 38 mg m^{-3} d^{-1}. Converted to sediment oxygen demand, the 1969/70 rate was 150 mg m^{-2} d^{-1} compared with the present rates of between 490 mg m^{-2} d^{-1} and 810 mg m^{-2} d^{-1}.

Figure No. 9

Time-series plot of the decrease in oxygen in the 20 m depth stratum in Lake Ototoa in spring 2005, using 15-minute interval data from the ARC oxygen data-logger. There was essentially no change in temperature during this period. The hypolimnetic oxygen depletion rate estimated from these data is 205 mg m^{-3} d^{-1} (r^2 = 0.9878).



4.1.3 Water clarity

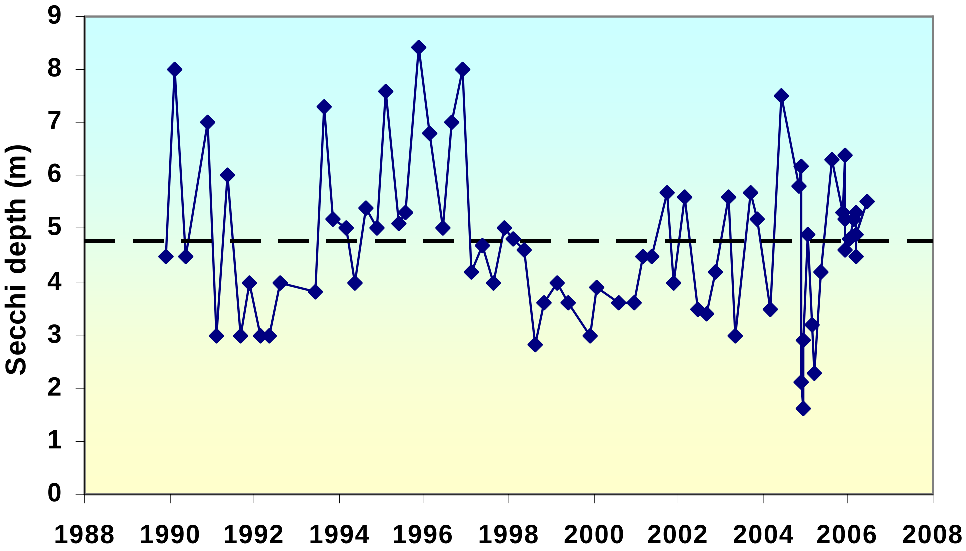
Water clarity as measured by Secchi disc depth was high but variable along the length of the lake on most occasions. On 5 December 2005, the tilt of the upper thermocline (Fig. 6) was accompanied by a difference in water clarity along the lake axis with the highest clarity (Secchi depth = 6.4 m) at the southern end, where the thermocline was deepest, and the lowest clarity (Secchi depth = 4.6 m) at the northern end.

In general the water clarity data measured during this study (mean 5.17 m, range 4.8 m to 6.4 m) were within the range of the long-term ARC monitoring data which has a large degree of variability around a mean clarity of 4.75 m (range 1.6 m to 8.4 m) (Fig. 10). While a regression through the whole data set since 1989 showed that there was no statistically significant trend in the data ($P = 0.3$, $r^2 = 0.015$, $n = 74$), the variability in the data had an apparent temporal cyclic pattern. Barnes & Burns (2005) also noted the cyclic pattern and an apparent correspondence with the El Niño Southern Oscillation (ENSO). This implies a link between regional climate and water clarity.

The factors affecting water clarity include dissolved organic carbon (colour e.g., "tea" staining), detrital particles including inorganic suspended solids, and living biota including algae and zooplankton. There was no obvious colouring of the lake water and no correlation between algal biomass and water clarity although there were some correspondences at times of peak biomass. The relationship between turbidity and water clarity was not consistent, with the data showing an apparent correspondence rather than a correlation on some occasions. (See Appendix 5 Clarity for more detail.)

Figure No. 10

Time-series plots of water clarity as indicated by Secchi disc depth showing the natural variability around a mean value of 4.75 m (broken line).



4.1.4 Chlorophyll *a*

Chlorophyll *a* results measured during this study taken from 5 depths in the lake ranged from 1.5 to 7.0 mg m^{-3} indicating that algal biomass, although not high, was highly variable both with depth and time across summer. (Fig. 11). These values were within the lower range of the long-term ARC chlorophyll *a* data from 1988 to present, which has a mean of 4.2 mg m^{-3} and a range from 0.6 to 19.5 mg m^{-3}.

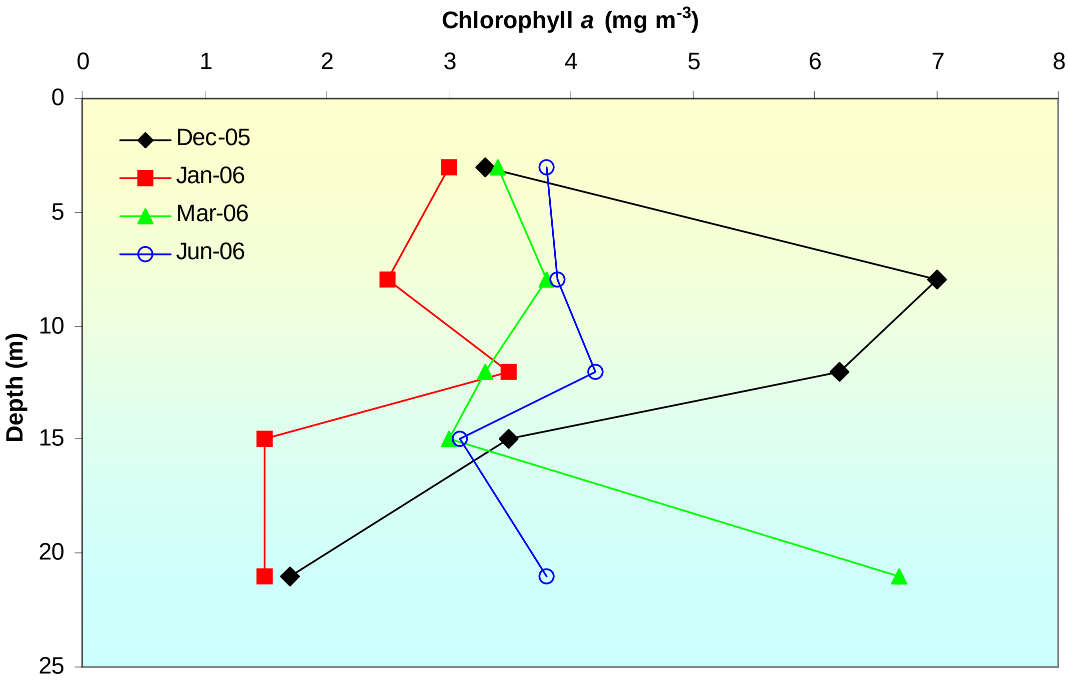
The changes in vertical distribution of chlorophyll *a* on the 4 sampling occasions were likely to be a function of in-lake processes associated with the physical structure of the lake. On the 3 occasions when the lake was thermally stratified, the algal biomass was constrained by the lower thermocline (Fig. 12). In December 2005, the algal biomass was distributed between the upper and lower thermoclines (Fig. 12A) although there appeared to be some sedimentation to the bottom.

As summer advanced, the algal biomass became more closely associated with the lower thermocline (January, Fig. 12B) and by March, the algae had developed a strong deep chlorophyll maximum (DCM) across the thermocline. (Fig. 12C; Appendix 6 - Chlorophyll). The algal species assemblage through the stratified period was dominated by dinoflagellates, *Peridinium sp.*, which are motile and can adjust their position in the water column to take advantage of the nutrients diffusing up through the thermocline and light from above.

After mixing, the nutrients from the hypolimnion would have been redistributed throughout the lake water column and the algal species assemblage was dominated by diatoms, *Aulacoseira sp*. and *Fragilaria crotonensis*, which were settling out of the water column in June 2006 (Fig. 12D).

Figure No. 11

Chlorophyll *a* concentrations at the mid lake monitoring station on the 4 sampling occasions.

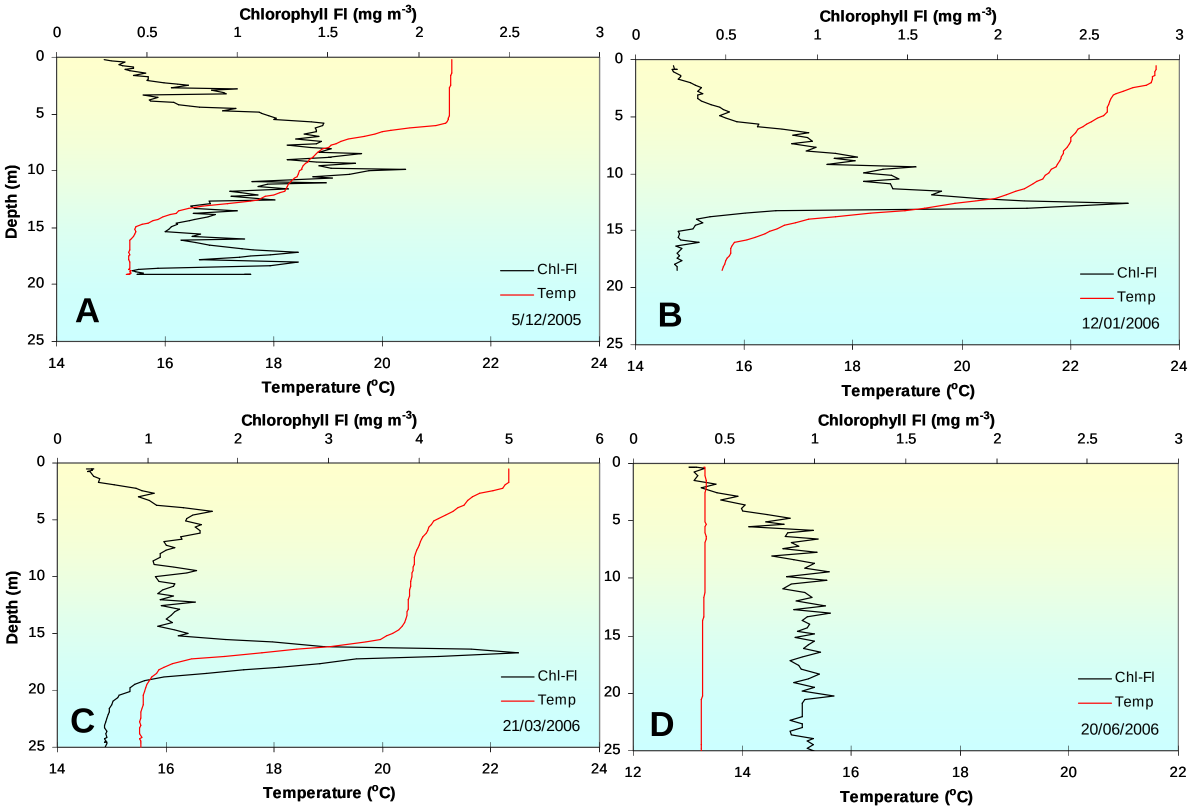


The development of a DCM is a characteristic of a high water quality lake. It is an indication that the upper water column is depleted in plant growth nutrients which would otherwise sustain algal growth that would shade the algae below and stop growth. With a Secchi depth of around 5 m, the photic zone is likely to extend down to about 15m, which coincides with the lower thermocline.

As the water below the thermocline becomes oxygen depleted, nutrients are released from the sediment and accumulate in the hypolimnion. Nutrients diffusing upwards through the thermocline can support the growth of algae in the thermocline and are supported in this low-light regime by its density gradient. The dominance of dinoflagellates is consistent with the DCM.

Figure No. 12

Chlorophyll fluorescence profiles relative to the thermal structure of Lake Ototoa on the 4 sampling occasions. Sections A, B, and C show the formation of a deep chlorophyll maximum on the thermocline while section D is after Autumn mixing.



4.1.5 Specific conductance

Consistent with CO_2, nutrient, and mineral release from the sediments, specific conductance profiles showed a sudden increase below the lower thermocline when the lake was thermally stratified. From December 2005 to March 2006, the specific conductance of the upper water column also increased suggesting an upwards diffusion of these compounds across the thermocline (See Appendix 7-Specific conductance for more details). This diffusive flux is likely to be a factor supporting the DCM.

4.2 Nutrients

The nutrient concentrations in Lake Ototoa were generally low and the measurements made on samples from the 4 visits were lower than those recorded in the early ARC monitoring data (see Appendix 2 Analytical comparison). Stream and groundwater nutrient concentrations were high as were the sediment porewater nutrient concentrations.

4.2.1 Lake

Nutrient data collected from 5 depths at the routine monitoring station on the 4 sampling occasions (Table 1) showed small changes over time in the concentrations of the parameters measured, especially for chlorophyll *a* , SS, DRP, and NH_4-N at 20 m depth. The chlorophyll *a* and SS concentrations increased together reaching a maximum in the 21 March 2006 data, which is consistent with the DCM being at a maximum at that time (Fig. 12C). The DRP and NH_4-N concentrations began to increase in the bottom waters after the hypolimnion became anoxic in December 2005. This was consistent with nutrient release from the sediments by decomposition processes. In June 2006, the sudden increase in NH_4-N concentrations throughout the water column is consistent with the dispersion of the nutrients that had accumulated in the hypolimnion when the lake mixed in winter. There was also a small increase in NO_3-N concentration in the lake water column which is consistent with nitrification of some of that NH_4-N.

Of interest is that DIN was still present a month after mixing when there was sufficient light for algal growth but DRP concentrations were extremely low.

Phosphorus concentrations as DRP in the lake water were consistently low during this study and the high N:P ratios typically >20:1 indicate that the lake was strongly P-limited for algal growth. This is consistent with the presence of DIN but no DRP in the water column in June 2006. The overall low TP and TN concentrations (Table 1) were consistent with a high water quality.

When sediment nutrient release occurs under anaerobic conditions, both NH_4-N and DRP are released from the sediment and should accumulate in the water column in the hypolimnion. However, if oxygen was still present in the hypolimnion (e.g., Fig. 8), the NH_4-N released should be nitrified to NO_3-N which could then be denitrified to N_2 gas and lost from the system. There was no apparent accumulation of NO_3-N in the hypolimnion which suggests that denitrification rates exceed nitrification rates.

The absence of high NO_3-N concentrations in the ARC data since 2000 and in the data from this study (<0.005 g m^{-3}) is in contrast to the high NO_3-N concentrations (average 0.35 g m^{-3}, range 0.12 to 0.6 g m^{-3}) reported in the 1969/70 study (Green 1975). However, the presence of elevated NO_3-N concentrations in the lake during summer 1969/70, is consistent with hypolimnion remaining aerobic in that year.

Once the hypolimnion had become anoxic and nitrification had stopped, NH_4-N released from the sediments begins to accumulate in the hypolimnion. The nutrient data (Table 1) show that NH_4-N concentrations increased from December through to March and April (ARC data). These high bottom water NH_4-N concentrations dispersed throughout the water column at lower levels in June after the lake had mixed. The NH_4-N concentrations in the hypolimnion in April 2006 were comparable with the NO_3-N concentrations reported in water column in 1969/70. This observation implies a lower mass of inorganic nitrogen in Lake Ototoa in 2006 than was present in the lake in 1969/70.

Table No. 1

Nutrient, chlorophyll *a,* and suspended solids data collected from 5 depths on the 4 sampling occasion as analysed by NIWA. (* DRP and, consequently, TP data may be affected by iron oxidation and precipitation after filtration).

Date	Depth (m)	Chl-a mg m^{-3}	SS g/m3	DRP* mg m^{-3}	DOP mg m^{-3}	PP mg m^{-3}	TP mg m^{-3}	NH_4-N mg m^{-3}	NO_3-N mg m^{-3}	DON mg m^{-3}	PN mg m^{-3}	TN mg m^{-3}	PC mg m^{-3}
6/12/2005													
	3	3.3	1.4	1	3	8.9	12.9	1	<1	213	66	280	490
	8	7.0	1.9	1	5	8.8	14.8	3	2	230	66	301	661
	11	6.2	2.0	1	4	7.5	12.5	2	1	221	56	280	537
	15	3.5	1.4	2	4	5.5	11.5	2	4	208	41	255	388
	21	1.7	2.1	4	5	5.6	14.6	3	3	209	61	276	485
13/01/2006													
	3	3.0	1.6	1	2	3.3	6.3	3	1	253	45	302	702
	8	2.5	1.4	3	4	2.8	9.8	4	1	272	37	314	451
	12	3.5	1.2	3	5	3.1	11.1	2	<1	229	42	273	536
	16	1.5	2.0	3	4	3.8	10.8	42	<1	236	51	329	481
	21	1.5	2.2	7	2	3.9	12.9	45	<1	213	44	302	461
20/03/2006													
	3	3.4	1.5	0.5	2	4.6	7.1	2	1	225	62	290	684
	8	3.8	1.3	0.5	3	3.5	7.0	2	1	221	47	271	499
	12	3.3	1.3	1	3	3.0	7.0	1	1	227	41	270	408
	15	3.0	1.2	1	3	3.0	7.0	2	2	226	41	271	395
	21	6.7	4.3	16	2	6.7	24.7	253	1	218	80	552	770
20/06/2006													
	3	3.8	0.9	0.5	3	5.0	8.5	12	5	228	66	311	613
	8	3.9	1.1	0.5	5	13.0	18.5	13	4	212	173	402	1596
	12	4.2	1.2	1	4	6.7	11.7	13	4	205	89	311	826
	15	3.1	1.2	0.5	4	5.7	10.2	13	4	213	63	293	698
	20	3.8	1.2	0.5	5	4.3	9.8	13	3	233	47	296	523

The sediment release rate of NH_4-N was estimated by combining the ARC monitoring data from other dates between November 2005 and June 2006 with the NIWA data and taking a regression slope of those data points on the linear part of the curve (Fig. 13). This method gave an estimated NH_4-N accumulation rate in the hypolimnion at 20 m from sediment release of 0.0031 g m^{-3} d^{-1} (r^2 = 0.9999) for a 90 day period. This accumulation rate was converted to an areal release rate using the NH_4-N gradient in the hypolimnion (Fig. 14) and the volume of the hypolimnion (Appendix 1, Table A1). Assuming the vertical nutrient gradient, estimated as 0.0626 g m^{-3} m^{-1} (Fig. 14), was similar across the whole lake bed, the areal sediment release rate was likely to be about 0.0021-0.0026 g m^{-2} d^{-1}.

Figure No. 13

Time-series ammoniacal nitrogen (NH_4-N) concentration changes at 20 m in the hypolimnion from November 2005 to June 2006 using both NIWA and ARC data. The regression line (off-set broken line) is for the 4 data points circled in red (from January to April 2006) and has a slope of 0.0031 g m^3 d^{-1} (r^2 = 0.9999).

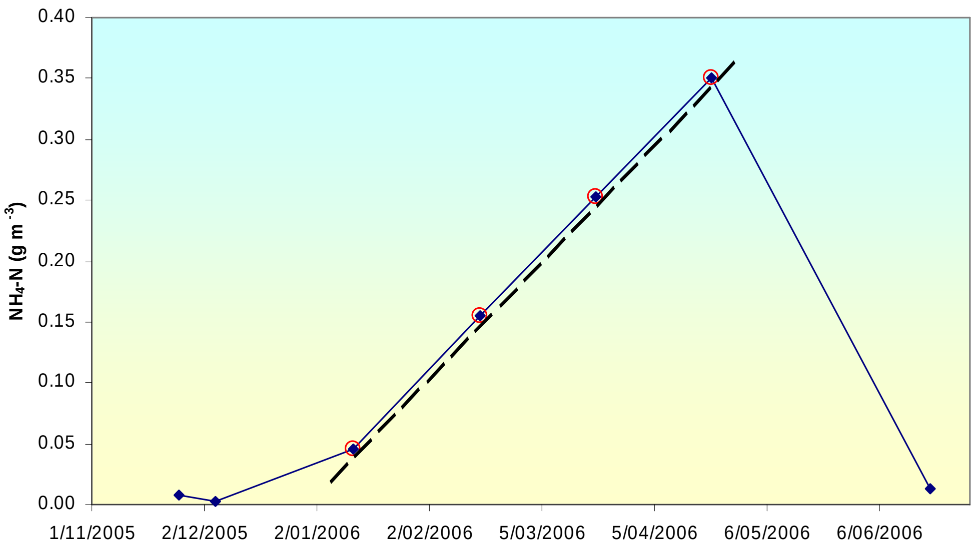
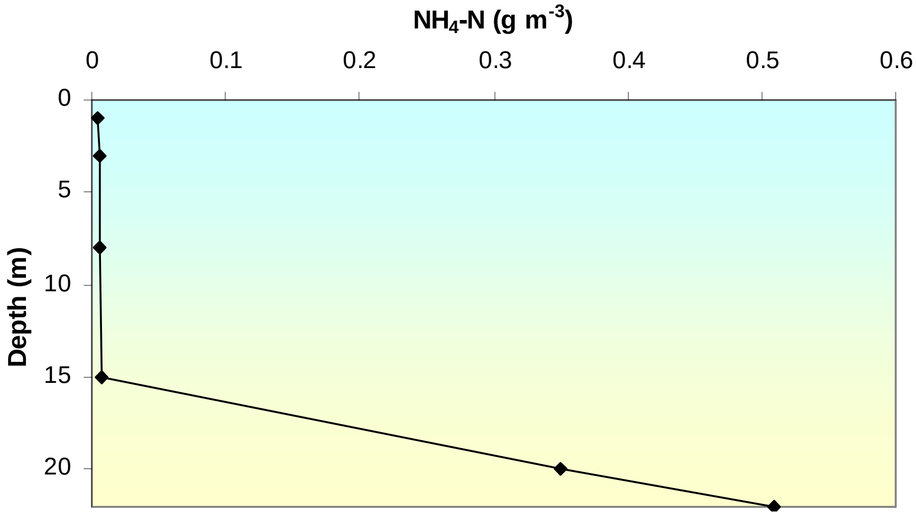


Figure No. 14

Vertical profile of ammoniacal nitrogen (NH_4-N) concentration changes with depth on 21 April 2006 (ARC data) at the mid-lake monitoring site. Thermocline at 15 m. The change in (NH_4-N) concentration is 0.063 g m^{-3} m^{-1}.



While the DRP concentrations also increased in the hypolimnion by a small amount, there is uncertainty about those concentrations due to the potential for iron flocculation of the DRP as the reduced iron oxidized under the aerobic conditions after filtration. Consequently, the DRP data have not been evaluated for sediment release rates.

Examination of the ARC long-term monitoring data since 2000 found a similar pattern of little change in DRP, TP, and NO_3-N concentrations at any depth, while the NH_4-N concentrations in the hypolimnion at 20 m increased through summer, after the lake had stratified.

Prior to 2000, the bottom sampling depths for the ARC monitoring data were not consistent. From 1988 to 1993 water samples were only collected from 0 and 10 m depths, and from 1994 to 1999, an extra sample was collected from about 15 –16 m. It was only since 2000 that bottom water samples were consistently collected from a depth of 20 m. Consequently, variability in the bottom water NH_4-N concentrations in data before 2000 may reflect the sampling depth relative to the NH_4-N concentration gradient in the hypolimnion (e.g., Fig. 14). A similar degree of variability in bottom water oxygen concentrations would also be expected (e.g., Fig. 8).

4.2.2 Sediment efflux measurements

4.2.2.1 Benthic chambers

The depletion of bottom water oxygen during summer stratification and the gradual accumulation of NH_4-N in the hypolimnion are the signatures of sediment processes that consume oxygen and release nutrients. To measure the nutrient efflux rates, the benthic chamber experiment confines a small volume of bottom water over an area of sediment. The changes over time in nutrient concentrations in the water enclosed in the chamber are then used to estimate the rates of release or uptake of each nutrient by the sediment.

The results showed no change in nutrient concentrations over the initial ambient water over a 24 hour period at the north and south ends of the lake in December 2005 and at the shallow western site in January 2006. For each of these experiments the water enclosed in the chamber was essentially devoid of the nutrients DRP, NO_3-N, and NH_4-N. However, at the deep mid lake monitoring site in January 2006 there was an increase in NH_4-N concentration of 17 mg m^{-3} in the chamber over the 23.75 hr incubation period.

From the chamber dimensions this change equates to an NH_4-N release rate of 2.75 mg m^{-2} d^{-1} which is comparable with the estimate of 2.1-2.6 mg m^{-2} d^{-1} based on the water column data (Section 4.2.1). Assuming this is a net input to the lake of N from internal recycling, this is equivalent to about 2100 g d^{-1} from the sediments below 15 m. While the efflux of DRP was not measured, based on the proportions of N and P in the sediment pore-water (Table 2) the DRP load from the sediments was likely to be about 100 g d^{-1}.

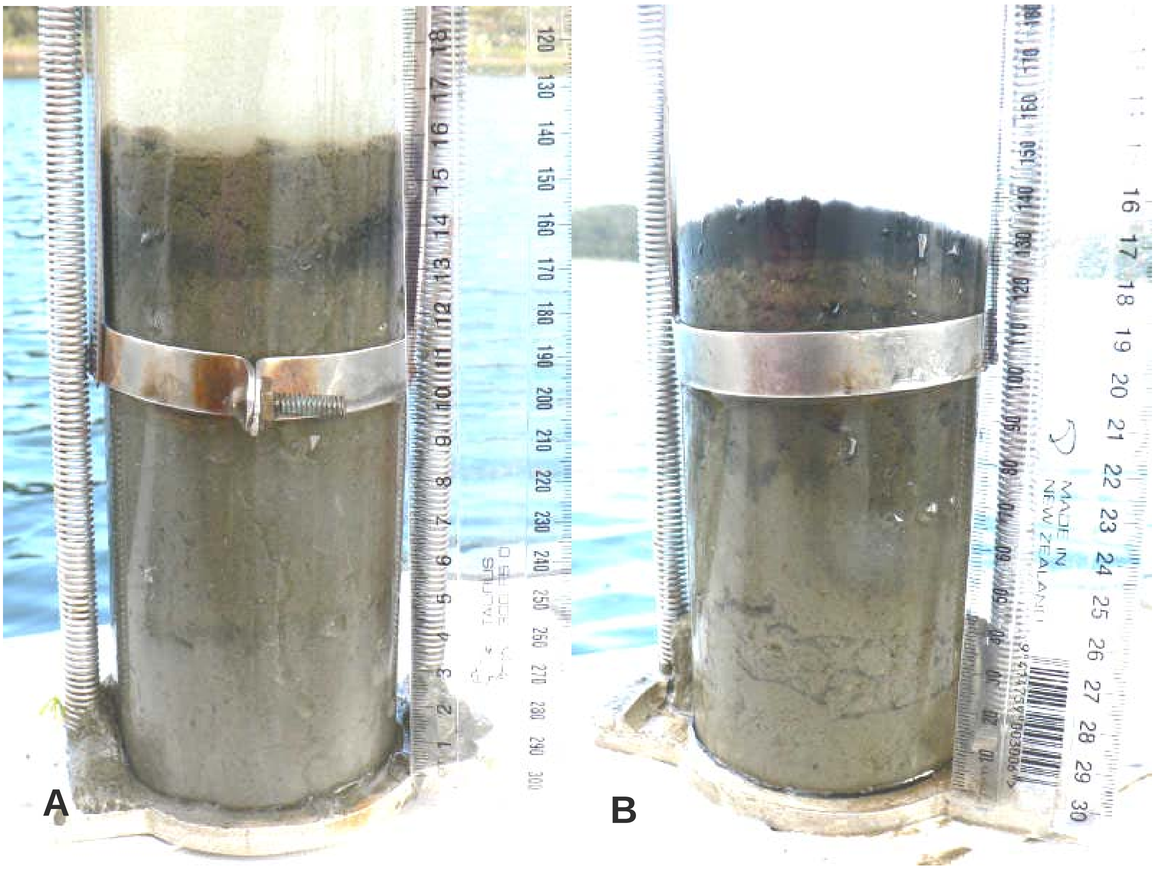
4.2.2.2 Sediment cores

Sediment collected with an Ekman dredge lost much of the surficial sediment layer on retrieval and hence may only reflect the sub-surface pore-water nutrient concentrations. The Jenkins corer, however, provided cores with an undisturbed sediment-water interface enabling a more detailed evaluation of nutrient concentrations across this boundary. The transparent core tube also revealed the structure of the sediment (Fig. 15). At the western 15-m deep site (Fig.15A) the organic sediment layer was about 11-cm thick over fine sand. The surface layer was relatively loose with a black layer about 1 cm below the surface. At the mid-lake 21-m deep monitoring site, the corer did not reach the fine sand layer and hence the organic layer was at least 13 cm deep. The core had a 1-cm thick cohesive jelly-like black layer of bacterial mucilage across the surface. The water above both cores smelt strongly of hydrogen sulphide consistent with the sediments being anoxic.

Concentrations of DRP, NH_4-N, and NO_3-N in the near-surface pore water (0-1 cm slice) of sediment from the 2 sites in the hypolimnion were about double the concentrations in the overlying water (Table 2). The pore water nutrient concentrations increased with increasing depth, reaching about 2000 mg m^{-3} for NH_4-N at a depth of 4-6 cm in the western core and a similar concentration at about 2 cm in the mid-lake core. The higher porewater NH_4-N concentrations closer to the sediment surface in the mid-lake core may reflect the presence of the gelatinous layer which would act as a diffusion barrier on the sediments at that site.

Figure No. 15

Sediment cores from A) the western site and B) the mid-lake monitoring site from Lake Ototoa on 21 March 2006.



The relatively low DRP concentrations in the porewater (Table 2) were consistent with the low DRP concentrations in the overlying water column and supports the conclusion that Lake Ototoa is P-limited. The reason for the low DRP is probably associated with the iron sand in the sediments and the ability of iron to sequester DRP from the water column.

Table No. 2

Pore water nutrient concentrations from sediment cores taken from 2 sampling stations relative to near bottom water nutrient concentrations on 21 March 2006. Samples collected by Jenkins Corer had an undisturbed sediment-water interface. Samples collected by Ekman Dredge lost part of the surface layer during retrieval but show a similar range of pore water nutrient concentrations as the Jenkins Corer sample from the mid-lake monitoring site.

Sampling site (Sampling method)	**Slice depth** (cm)	**DRP** (mg m^{-3})	**NH_4-N** (mg m^{-3})	**NO_3-N** (mg m^{-3})
Bottom lake water		<1	253	1
West side site (15m)				
(Jenkins corer)	0-1	8	550	10
	1-2	28	654	28
	2-3	16	1040	12
	3-4	6	1358	6
	4-6	10	2160	10
Mid-lake monitoring site (21m)				
(Jenkins corer)	0-1	4	782	2
	1-2	20	1850	12
	2-4	14	2380	8
Mid-lake monitoring site (22m)				
(Ekman Dredge)	0-1	2	3120	10
	1-2	4	2160	2
	2-3	30	3200	18
	3-4	28	1150	32

4.2.3 Sedimentation

Sediment trap data (Table 3) showed that the downward fluxes of particulate matter, as indicated by SS, ranged from 0.97 to 3.2 g m^{-2} d^{-1} in the upper water column and 1.4 to 3.6 g m^{-2} d^{-1} at 1 m above the lake bed. If in-lake production was the main source of particulate matter in a lake, the expectation would be for sedimentation rates to increase with depth unless the water column was fully mixed (Table 3, June 2006 data). Under stratified conditions (Table 3, December 2005, January and March 2006 data), the expected increase in SS sedimentation rates with depth should have been related to algal production in the water column between the upper and lower traps and sediment resuspension (Gibbs 2001) or sediment focusing of shallow sediments into deeper water.

During the detailed study of Lake Ototoa, the lake was thermally stratified on the first three visits and algal production occurred in the water column between the upper and lower sediment traps as indicated by the formation of a DCM which concentrated at about 17 m on 21 March 2006 (Figs. 12). However, the sedimentation rates were substantially higher in the upper than lower traps in January suggesting a recent increase in surface algal production or another source of particulate material about the time of that sampling.

Table No. 3

Sedimentation rates (mg m^{-2} d^{-1}) at depths of 8m and 21m at the mid-lake monitoring site on the 4 study occasions. Settling velocities (SV) are calculated at each depth for the total suspended solids component. Sedimentation rates are calculated at each depth for the total suspended solids component and the proportions of carbon, nitrogen, and phosphorus in the suspended solids. Ratios of C:N:P are gram equivalent masses normalised to phosphorus as 1.

Date	SV (m d^{-1})	Sedimentation rates (mg m^{-2} d^{-1})					Ratios		
Trap depths	SS	SS	PC	PN	PP	C:SS	C	N	P
5-6Dec 2005									
(Light northerly breeze)									
8m	0.8	1523.0	634.0	72.3	9.7	0.42	65	7	1
21m	0.8	1737.6	606.3	61.4	5.6	0.35	108	11	1
12-13 Jan 2006									
(Southerly breeze)									
8m	1.5	2064.0	1160.8	75.8	5.7	0.56	205	13	1
21m	0.5	1388.3	420.7	39.2	3.5	0.30	119	11	1
20-21 Mar 2006									
(Light southerly breeze)									
8m	0.7	970.8	343.5	28.3	2.1	0.35	163	13	1
21m	0.4	1828.3	863.0	39.4	3.3	0.47	261	12	1
19-20 Jun 2006									
(Southerly storm)									
8m	2.1	3157.0	814.2	76.6	5.8	0.26	141	13	1
21m	2.8	3603.4	705.9	63.3	5.8	0.20	122	11	1

Throughout the 2005/06 summer stratified period, the algal population was dominated by the dinoflagellate, *Peridinium sp.* (Appendix 8 - Sedimentation; Fig. A8.1) which, being motile, may have influenced the trap data. To determine whether the algal biomass alone accounts for the measured sedimentation rates, the carbon, nitrogen, and phosphorus stoichiometry of the trapped material was evaluated relative to expected C:N:P ratios for algae.

Algal production results in the formation of chlorophyll which has an atomic ratio for C:N:P of 106:16:1 (Redfield 1958) i.e., the "Redfield ratio" which give C:N:P ratios of 41:7.2:1 by weight. While diatoms have silica sheaths and a low carbon to cell volume, dinoflagellates have a carbon thecae and thus a much higher carbon to cell volume (Menden-Deuer & Lessard 2000). The higher C content with the 7:1 N:P ratios from the sediment trap data in December 2005, indicate that the suspended solids in the upper water column were largely dominated by live algal cells associated with the dinoflagellate bloom. As dinoflagellates continued to dominate the algal assemblage through the stratified period, the expectation would be for C:N:P ratios similar to the December 2005 values in January 2006 if the higher sedimentation rates in the upper water column were associated with a recent increase in algal production. However, the ratios were very different implying another source of particulate matter.

In his 1969-70 study of Lake Ototoa, Green (1975) noted a negative correlation between water clarity in the lake and wind speed in the previous 5 days. He suggested that this was caused by "*windblown material from nearby dunes*" i.e., and Aeolian input. That explanation is still plausible with higher proportions of fine material being blown into the lake when the catchment is very dry in summer and / or the winds are strong from the south-west across the coastal sand dunes. Another explanation is that the sediments on the littoral zone lake bed down to at least 8 m were being re-suspended by in-lake currents associated with the tilting of the upper thermocline (Fig. 6) in response to the southerly breeze. However, because a similar tilting observed in the opposite direction for a light northerly breeze in December did not produce the same degree of SS in the 8 m trap, it is likely that at least part of the trapped material in January 2006 was new material blown into the lake by the wind rather than from the littoral zone.

The high SS and PC sedimentation rates at 8 m in the January 2006 samples coincided with very dry conditions and persistent southerly breezes. Microscopic examination of the material from the 8-m trap showed a higher proportion of both fine sand grains and pollen than in the material from the 21-m trap at that time or the 8-m trap material from December 2005 (Appendix 8 – Sedimentation; Fig. A8.1). The pollen appeared to be mainly from grasses rather than being pine pollen from the adjacent pine forest.

The much higher SS and PC sedimentation rates at both depths in June 2006 coincided with a southerly storm when high rainfall caused overland flow with pasture runoff flowing directly into the lake (Section 4.2.4). The strength of the wind was likely to have caused significant sediment resuspension from depths of at least 15 m in the lake as well as carrying new material into the lake. Microscopic examination of the material from these traps (Appendix 8 - Sedimentation, Fig. A8.2B, Fig. A8.3) showed large amounts of sand with large amorphous lumps which were probably re-suspended sediment. The trap material had few pollen grains but substantial quantities (>70%) of diatoms, mainly *Aulacoseira granulata* and *Fragilaria crotonensis*, probably associated with the algal proliferation after winter mixing.

The C:SS ratios were highest in the 8-m sample in January 2006, consistent with the elevated pollen levels and dinoflagellates in that sample, and were lowest in June 2006, consistent with the high proportion of inorganic sand and diatoms in the trapped material.

Settling velocities of the SS in the upper water column on 12 January 2006 and at both depths on 21 June 2006 were extremely high (Table 3) consistent with a high proportion of sand in the trapped material.

Although there were several old slip faces on the western side of the lake, especially in the native forest along the stream arm, no fresh slips were observed during the storm event.

4.2.4 Inflows

The stream flow was reasonably consistent and visually estimated to be about 10-15 litres s^{-1} except during the storm event when the flow was higher at around 20 litres s^{-1}. The highest non-storm event flow was in December 2005 following a wet spring.

Groundwater inflows are likely to be small as the lake catchment width is small except at the northern end. Based on the stream inflow, catchment area, and mean annual rainfall since 1988 (1198 mm[1]), and assuming evapotranspiration of 800 mm yr^{-1}, the average shore line groundwater inflow was estimated to be in the order of 0.006 Litres s^{-1} m^{-1} or about 500 litres d^{-1} per metre of lake shore. During the summer water deficit period, the water table moved down to at least a metre below the surface of the lake indicating a net water loss to the groundwater from the lake rather than an inflow, at that time.

Nutrient concentrations in the surface stream and groundwater inflows were higher in nitrogen than phosphorus (Table 6). The stream water was aerobic with NO_3-N concentrations of 200-430 mg m^{-3} and DON concentrations of 160-280 mg m^{-3}. DRP and DOP concentrations were 5-8 mg m^{-3} and 8-22 mg m^{-3}, respectively. Highest N and P concentrations in the stream occurred during the storm event in June, possibly reflecting surface runoff from the bush and scrub land or enhanced leaching of the soil. Surface runoff from pasture on that day had little DRP and <100 mg m^{-3} of NO_3-N (Table 4).

Table No. 4

Stream inflow and groundwater nutrient concentrations from 5 locations around Lake Ototoa over summer and autumn 2005/2006. Particulate nutrients are not measured in groundwater. No sample from 3 sites on 12 January 2006. Missing DOP and DON values not measured. (O/Flow = overland flow)

Site	Date	DRP	DOP	TP	NH_4-N	NO_3-N	DON	TN
Stream		mg m^{-3}	mg m^{-3}	mg m^{-3}	mg m^{-3}	mg m^{-3}	mg m^{-3}	mg m^{-3}
	5/12/2005	8	8	18	4	361	207	601
	12/01/2006	7	7	18	8	208	244	486
	20/03/2006	4	9	15	1	272	159	465
	20/06/2006	5	22	29	18	431	275	741
Groundwater								
Ramp	5/12/2005	33	1		313	4	434	
(Western)	12/01/2006							
	20/03/2006	1			361	1		
	20/06/2006	2			104	<1		
South end	5/12/2005	14	36		119	<1	264	
(Southern)	12/01/2006							
	20/03/2006	1			31	<1		
	20/06/2006	9			4	<1		
House	5/12/2005	48	1		78	5	482	
(Eastern)	12/01/2006							
	20/03/2006	2			347	<1		
	20/06/2006	1			13	1		
O/Flow	20/06/2006	1			6	88		
Park	5/12/2005	24	32		153	15	1092	
(N'Eastern)	12/01/2006	1	2		60	2	504	
	20/03/2006	1			402	<1		
	20/06/2006	<1			137	<1		
Shed	5/12/2005	11	20		36	34	459	
(Northern)	12/01/2006	2	6		35	<1	376	
	20/03/2006	1			660	1		
	20/06/2006	1			<1	1		

[1]Rainfall data from the recording met station at Mairetahi, Agent No. 1377, 36.55678° S, 174.31963° E about 10 km from Lake Ototoa, on the South Kaipara Head

The groundwater samples were difficult to obtain at the southern sites in mid summer due to the small catchment and low water tables.

In general, nutrient concentrations were highly variable between sites and between samplings. In December 2005 the groundwater was anaerobic which presumably allowed DRP bound to mineral iron to mobilize and consequently the DRP concentrations on that date were high. Under aerobic conditions on subsequent samplings the DRP concentrations were low. Dissolved nitrogen components had high concentration variability with NH_4-N and DON concentrations of <1-660 mg m^{-3} and 260-1090 mg m^{-3}, respectively (Table 4). Lowest nutrient concentrations occurred during the storm event (June 2006) which may indicate dilution by local rainfall infiltration or dilution caused by the intrusion of lake water into the surface aquifer as the lake level rose. All samples were taken by the groundwater sampling penetrometer at least 0.5-m below the soil surface, which would normally exclude surface runoff as a diluent.

An estimate of the nutrient loads on the lake from the stream calculated from the average TN and TP values and using a mean inflow of 15 L s^{-1} was 720 and 26 g d^{-1}, respectively for the whole study period (December to June). Based on averaged concentrations from the 5 groundwater sites but excluding the data during the storm in June 2006, and using the mean flow of about 500 L d^{-1} per meter of lake shore (length of shore about 9 km), the estimate for the groundwater derived nutrient loads was about 1000 g DIN d^{-1} and 72 g DRP d^{-1}. The groundwater had a large component of dissolved organic nitrogen (DON) amounting to about 2300 g DON d^{-1}. This high ratio of N:P highlights the low phosphorus inputs from the catchment to the lake, emphasizing the P-limited status of the lake.

While these estimates of catchment nutrient loads suggest a substantial input of TN and a lesser input of TP to the lake, the DIN and DRP components of these inputs are unlikely to have a direct impact on lake water quality because they have to pass through a continuous buffer zone of emergent wetland plants to reach the open waters of the lake. Also, although the point source input from the stream contributes about 25% of the catchment TN drainage to the lake, the location of the stream at the head of the long narrow arm (Fig. 1) may prevent a rapid mixing of the stream water, and consequently those nutrients, with the lake.

4.3 Summary of flux rates

The data collected in this study have produced a number of flux estimates and these are summarized (Table 5).

Table No. 5

Summary of flux rates for Lake Ototoa estimated from this study on the 4 sampling occasions. Sediment release is from the whole lake bed below 15 m.

DATE	**Units**	**05 Dec 2005**	**12 Jan 2006**	**21 Mar 2006**	**20 Jun 2006**
Conditions		Fine	Fine	Fine	Raining
Wind		Light Northerly	Southerly breeze	Light Southerly	Southerly storm
FLUX					
Oxygen depletion					
Hypolimnetic (HOD)	mg m^{-3} d^{-1}	205			
Sediment demand (AOD)	mg m^{-2} d^{-1}	810			
Stream inflow (Table 6)					
Volume (estimate)	m^3 d^{-1}	1296	864	864	1728
TN	g d^{-1}	780	420	400	1280
TP	g d^{-1}	23.3	15.5	13.0	50.1
Sediment release					
N	g d^{-1}			2100	
P	g d^{-1}			100	
Sedimentation (Table 5)					
Suspended solids (SS)	mg m^{-2} d^{-1}				
8 m		1520	2060	970	3160
21 m		1740	1390	1830	3600
Particulate carbon (PC)	mg m^{-2} d^{-1}				
8 m		630	1160	340	810
21 m		610	420	860	710
Particulate nitrogen (PN)	mg m^{-2} d^{-1}				
8 m		72	76	28	77
21 m		61	39	39	63
Particulate phosphorus (PP)	mg m^{-2} d^{-1}				
8 m		9.7	5.7	2.1	5.8
21 m		5.6	3.5	3.3	5.8
Whole lake (surface area = 1.623 x 10^6 m^2)					
SS	kg d^{-1}	2467	3343	1574	5129
C	kg d^{-1}	1022	1883	552	1315
N	kg d^{-1}	117	123	45	125
P	kg d^{-1}	16	9	3	9