5 Discussion

The data collected during this study provide additional information to the ARC monitoring data since 1988 and earlier data collected by Green in 1969/70. The new data indicated that Lake Ototoa has high water quality characterised by high clarity and the formation of a deep chlorophyll *a* maximum during summer. However, while the lake thermally stratified in October and mixed in April the following year and has been described as monomictic (Green 1975), the data from this study showed that it also mixed several times for short periods during spring and early summer during strong wind events. This feature allowed heat and dissolved oxygen to move down into the hypolimnion and, presumably, allowed nutrients from the hypolimnion to mix up into the surface waters. Where this brief wind-induced mixing has occurred in other more eutrophic northern dune lakes (e.g., Lake Kapoai, NIWA unpublished data), the mixing event was usually followed by a rapid increase in algal production. Such responses were not seen in Lake Ototoa, which indicated that nutrient concentrations in the hypolimnion were low, and consistent with a high water quality.

5.1 Declining water quality

Although there are indications that the water quality of Lake Ototoa has declined recently (Barnes & Burns 2005), there are also conflicting indications that the water quality has not changed significantly in the last 17 years (de Winton et al. 2005) and that there have been changes which may have been cyclic (Barnes & Burns 2005; Duggan & Barnes 2005). The fundamental questions therefore are:

- Have there been changes in the water quality of the lake?
- If there were any changes, what was the time-scale of that change? i.e., were the changes “trends” or part of a cycle, or were they driven by events?
- Are internal nutrient loads a major factor in any changes in water quality?
- What management options could be used to ameliorate the effects of any changes on the lake?

5.1.1 Have there been any changes?

Barnes & Burns (2005) concluded that the water quality of Lake Ototoa was declining because 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*”. However, there is a concern about drawing a linear regression through time-series data which are acknowledged to have a cyclical pattern. For example, Barnes & Burns (2005) noted an apparent cyclical pattern in 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."

This conclusion suggests that the use of linear regressions of PAC and TLI may not be appropriate measures of change in Lake Ototoa.

Another concern is the validity of the data used to generate the TLI for each parameter. A review of the ARC data up to 1998 (Gibbs et al. 1999) found deficiencies in the overall dataset which may affect the results obtained by Barnes & Burns (2005). (See Appendix 2 – Analytical comparison)

Barnes & Burns (2005) commented 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*". Their "trend" in the TP data of 0.60 mg m^{-3} yr^{-1} is substantially less than the analytical precision of 10 mg m^{-3} in the ARC data set.

While the Barnes & Burns (2005) conclusions that the water quality is declining may not be strictly valid in terms of linear trends, there are other indications from the historical data that show there has been a change in water quality in the last 36 years.

5.1.1.1 Oxygen depletion

Evidence of change is seen in the extent of hypolimnetic oxygen depletion and the rate of that depletion in 2006, compared with the detailed survey by Green (1975) in 1969/70. In summer 1970, minimum oxygen concentrations were 2.3 g m^{-3} but in 2006 the hypolimnion became anoxic in summer. The oxygen depletion rate in the hypolimnion is presently between 124 and 205 mg m^{-3} d^{-1}. This indicates a considerably poorer water quality in 2006 than in 1969/70 when the estimated oxygen depletion rate was 38 mg m^{-3} d^{-1} (Green 1975).

The change from an aerobic to anoxic hypolimnion was accompanied by a change in the form of the dissolved inorganic nitrogen from NO_3-N, which was present in 1969/70, to NH_4-N, which was the dominant form measured in 2006. Maximum concentrations of NH_4-N in the hypolimnion in 2006 were comparable with averaged NO_3-N concentrations in the water column in 1969/70.

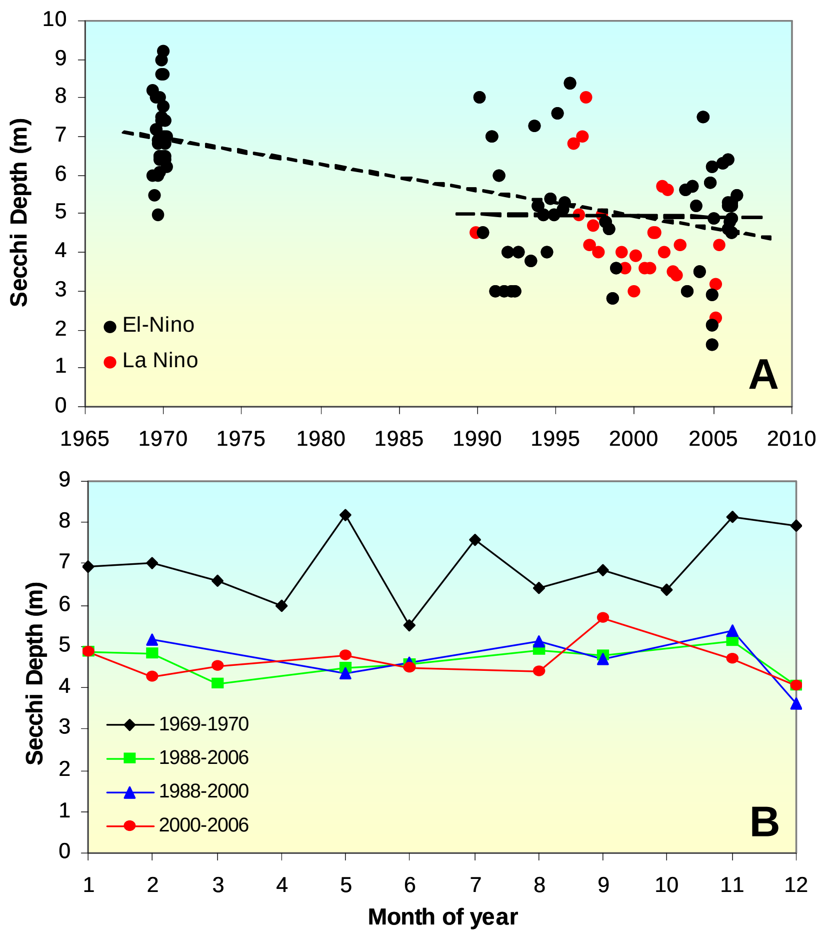
These data demonstrate that a change has occurred but, because of a lack of monitoring between 1970 and 1988, it is not possible to determine when key events such as bottom water anoxia first occurred. Consequently, it is also not possible to determine whether the change was a gradual "trend" or a "step-wise" response to one or more events.

5.1.1.2 Water clarity

The second key indicator of reduced water quality in Lake Ototoa is water clarity as indicated by Secchi depth (Fig. 16) and is one of the indices used by Barnes & Burns (2005). While the trend lines drawn through all data (including the historical 1969/70 data) and through the data since 1988 (Fig. 16A), indicate a gradual decrease in water clarity, the slopes are different with less slope in the regression through the ARC data since 1988. The regression slope for all data is strongly influenced by the historical data and hence the "trend" indicated by the linear regression slope through the whole dataset might be biased by the 1969/70 data. However, while the 1969/70 data were for a single year, and it is unknown whether that was a typical year, they are consistent with a single Secchi depth value of around 9 m in February 1950 (Cunningham et al. 1953) (Appendix 1).

Figure No. 16

Comparison of water clarity data between present and the 1969/70 study (Green 1975). A) Time-series changes (regression lines – see text), and B) mean Secchi depths by month of year. In part A, the data from El Niño and La Niña years are distinguished by black or red dots, respectively.



The apparent trend in the whole data set may also be strongly influenced by the paucity of data through each year since 1988 (4 samples) in comparison to the weekly measurements in 1969/70. To overcome this potential problem, the ARC clarity data have also been compared with the 1969/70 data using the mean data by month for selected time periods (Fig. 16B). These results clearly demonstrate that there is a significant difference between the 1969/70 data (mean 7.06 m) and the data since 1988 (mean 4.75 m) with a decrease of 33% in water clarity.

However, the mean monthly data from 1988 to 2000 (mean 4.70 m) was not significantly different from the mean monthly data from 2000 to 2006 (mean 4.64 m), which suggests that the change in water clarity may have been event or climate related rather than a typical linear trend, as noted by Barnes & Burns (2005), and that it most likely occurred between 1970 and 1988.

5.1.2 Trend or event driven change?

New Zealand lakes are thought to be affected by climatic events such as the ENSO, a 1 to 2 year cycle, and the Interdecadal Pacific Oscillation (IPO), a longer term cycle underlying the ENSO. Under the El Niño influence of ENSO, there are generally more westerly to south-westerly winds with higher rainfall, especially north of Auckland. Under the La Niña influence, there are generally more north-easterly winds. A plot of the frequency of El Niño and La Niña weather patterns since 1950 (Fig. 17) shows that during the period before 1977, the climate was dominated by mainly La Niña weather patterns but after 1977 the climate was dominated by El Niño weather patterns. This ENSO switch also coincided with a switch in the IPO around 1979/80 from negative to positive.

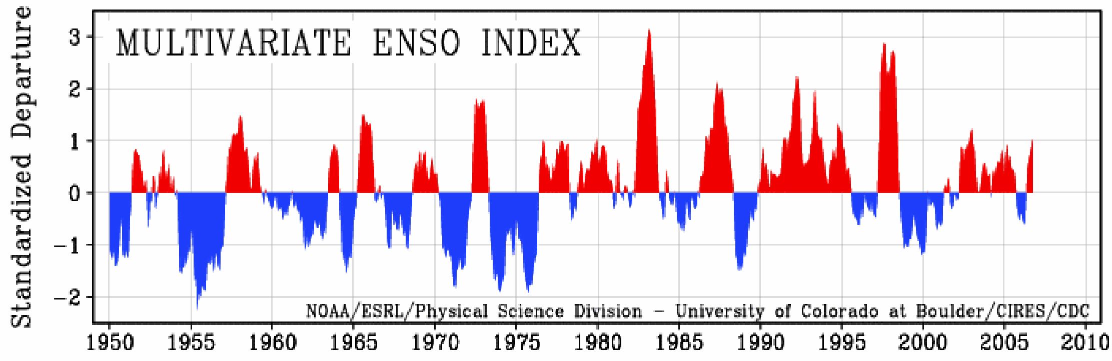
While this climate switch falls in the period when a change in water quality was most likely to occur, there may have been other factors, including changes in land use, which would also have an affect on water quality of the lake. For example, harvesting of the pine forest on the western side of Lake Ototoa began in 1997/98 (Fig. 2) and, because production forestry typically has a 20-25 year rotation from planting to harvest, it is possible that the land on the western side of the lake was cleared and planted in pine forest in the early 1970s.

The timing of that change in land use may be a key to understanding the cause of the change in water quality in the lake.

Plotting time-series of mean annual Secchi disk depth and the ENSO index between 1988 and 2005 (Fig. 18) showed that there was a significant correspondence between Secchi depth and the ENSO index from 1999 to 2005 ($p = 0.067$, $r^2 = 0.52$, $n = 7$), but no correspondence between these variables before 1999 ($p > 0.7$, $r^2 = 0.01$, $n = 10$). Consequently, the correspondence between Secchi depth and the ENSO index from 1999 to 2005 may be coincidental or it may indicate that climatic effects become more important from time to time.

Figure No. 17

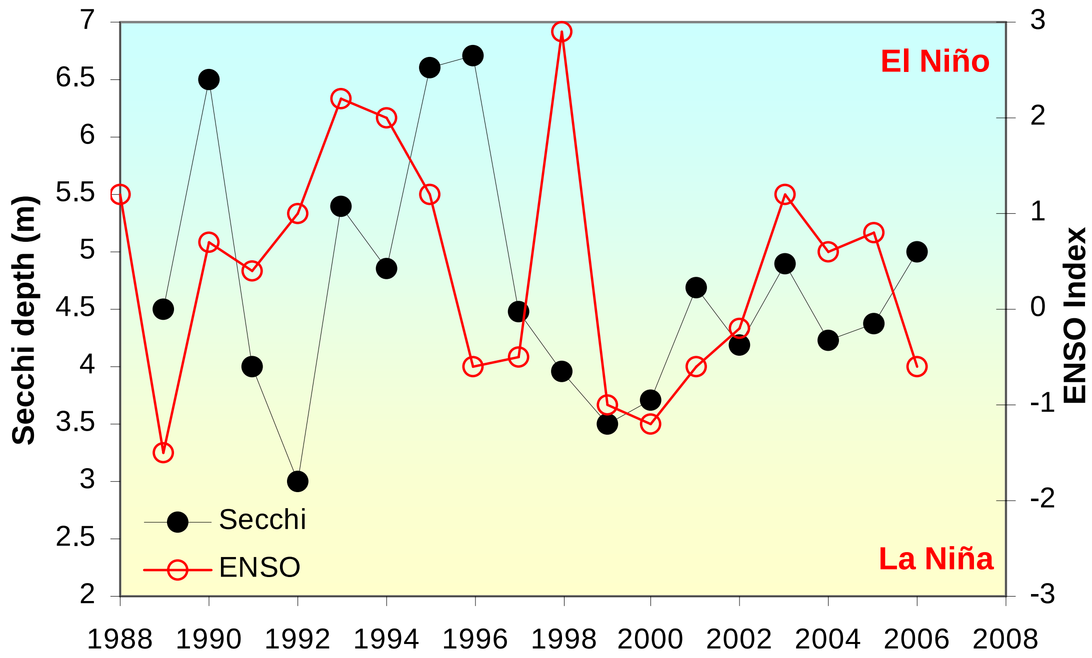
Historical record of the El Niño Southern Oscillation (ENSO) index since 1950. Web data from NOAA/ESRL/Physical Science Division as per the reference on the figure.



Although Lake Ototoa may be directly influenced by the cyclical patterns of climate and especially with wind (speed and direction) and rainfall intensity associated with the shift between El Niño and La Niña weather patterns, the lack of consistency in the long term ENSO correspondence indicates that other factors may also be affecting lake clarity.

Figure No. 18

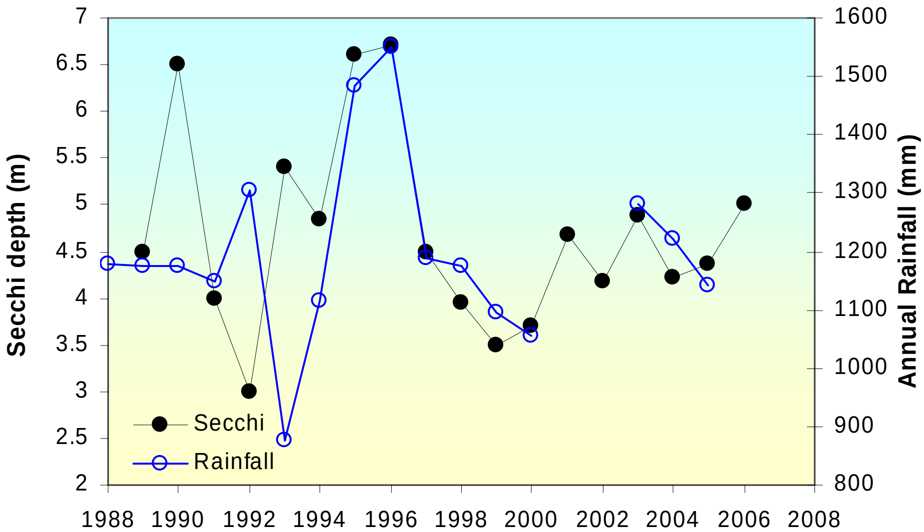
Correspondence between mean annual Secchi disc depth (ARC data) and the El Niño Southern Oscillation (ENSO) index was good after 1999 but poor before 1999. (Note: Secchi data are means of 3 or 4 measurements per year.)



One factor identified was local rainfall (Fig. 19). However, instead of there being an inverse relationship indicating increasing sediment loading with increased rainfall, there was a highly significant positive relationship between mean annual Secchi depth and annual rainfall on the lake for the period from 1994 to 2006 ($p << 0.001$, $r^2 = 0.872$, $n = 10$).

Figure No. 19

Relationship between mean annual Secchi disc depth (ARC data) and annual rainfall was statistically significant from 1994 ($p << 0.001$, $r2 = 0.872$, $n = 10$). Rainfall data from Mairetahi, Agent No. 1377 about 10 km from Lake Ototoa, on the South Kaipara Head.



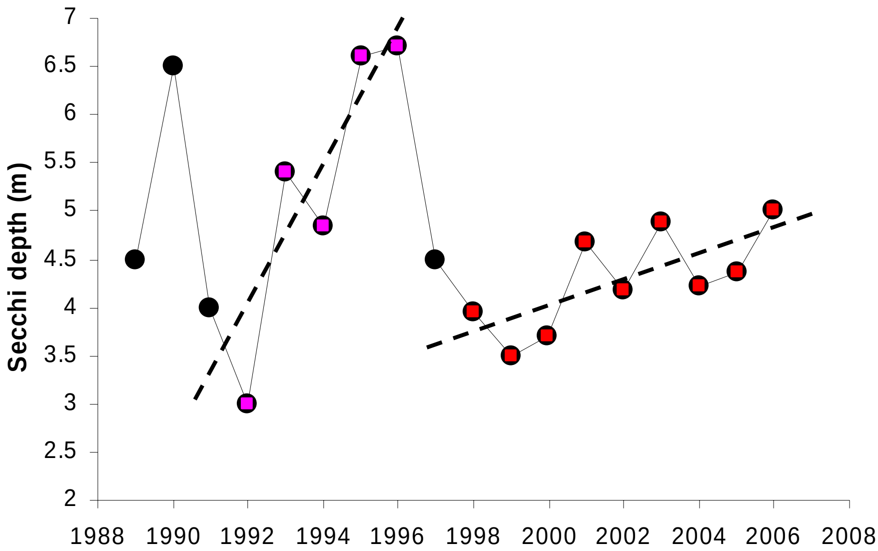
This unusual relationship may be interpreted as an indication that the higher rainfall years produced higher lake levels (no lake level data) with a concomitant reduction in sediment disturbance by wind events. However, coupled with the change in the predominant wind direction from north-easterly (i.e., across pasture land) to westerly (i.e., across the sand dunes) following the ENSO switch after 1977, the higher rainfall may also have reduced windblown terrigenous material, including soil and sand (Aeolian inputs), entering the lake by damping down the bare soil in the catchment.

Other possible explanations for the variability in the mean annual Secchi depth data include discrete “events” which increased lake turbidity and were followed by a period of recovery. The mean annual Secchi data (Fig. 20) show two periods, one in 1991 and the other in 1997, when Secchi depths and thus water clarity fell rapidly and markedly. While it is unknown what caused the fall in clarity in 1991, in 1997 the fall in water clarity may be related to production forest logging operations close to the lake which included the clear-felling of a compartment of pine trees on the western shores of the lake in 1997/98. While the positive correlation between water clarity and high rainfall precludes sediment run-off to the lake, in low rainfall periods the exposed soil after clear-felling would be prone to wind erosion increasing the Aeolian input to the lake. The slow recovery of water clarity from 1998 to 2006 may reflect the continued

Aeolian inputs from other parts of the adjacent forest which are still being harvested further from the lake.

Figure No. 20

Variability in mean annual Secchi disc depth (ARC data) with possible events in 1991 and 1997 followed by recovery periods (broken lines).



While the water clarity data have demonstrated changes in lake water quality, it is apparent that these are not part of a trend although identifying the cause of the changes is not easy. From the data presently available, it is likely that a number of factors including catchment effects (e.g., forestry) and variations in annual rainfall contributed to a large "step-wise" change in water clarity between 1970 and 1988 rather than that change being a linear trend. Since 1990 the lake appears to have experienced at least two, possibly Aeolian, events from which it is still recovering.

These conclusions are in contrast to the findings of Barnes & Burns (2005) who suggested that "*the decline in water clarity appeared to be driven by an increase in phytoplankton abundance due to increasing levels of inorganic nitrogen*".

Evaluation of the ARC lakes monitoring data showed no correlation between algal cell counts or chlorophyll *a*, as an indicator of phytoplankton biomass, and water clarity. (See Appendix 5 – Clarity). There was, however, a slight increase in inorganic nitrogen concentration in the epilimnion of 0.7 ± 0.62 mg m^{-3} yr^{-1} ($p < 0.05$, $r^2 = 0.037$, $n = 135$) which is comparable with the 0.6 mg m^{-3} yr^{-1} increase in TP found by Barnes & Burns (2005). However, these increases are substantially less than the analytical detection and reporting level of 10 mg m^{-3} and are unlikely to stimulate a significant increase in algal abundance even if they were real.

5.2 Nutrients: internal cycling or catchment inputs

5.2.1 Suspended solids and particulate carbon

Data collected from the sediment traps during this study indicated that there was an increased amount of organic and inorganic material in the upper water column associated with strong westerly winds. While most of that material was likely to be from internal re-suspension, the trapped material also includes the Aeolian component. If a quarter of the average PC load in the upper sediment traps (i.e., 25% of 735 mg m^{-2} d^{-1}) was from an external source blown into the lake, this would increase the sediment oxygen demand by around 490 mg m^{-2} d^{-1}. Compared with the sediment oxygen demand of 150 mg m^{-2} d^{-1} in 1969/70, which had the oxygen concentrations in the hypolimnion down to 2.3 g m^{-3}, an additional 490 mg m^{-2} d^{-1} would have been more than enough to cause the hypolimnion to go anoxic during summer stratification. A continuation of that input would perpetuate the occurrence of hypolimnetic anoxia in subsequent years.

The large expanse of exotic pine forest on the western side of the lake is a potential source of large amounts of wind-blown carbon[2] in the form of pollen in spring and other plant debris when the forest was harvested. No pine pollen was found in any of the sediment trap material on any date during this study, suggesting that either sediment re-suspension was not the major source of the material in the sediment traps or that sediment focusing had moved the spring pollen input to the deeper parts of the lake. Alternatively, fresh wind blown sand and dirt inputs may have buried the pollen since the spring input, which would imply a rapid sediment accumulation rate (SAR) in the lake.

Estimating the Aeolian load, if a quarter of the average trapped SS material (i.e., 25% of 1.95 g m^{-2} d^{-1}) was wind blown sand and assuming a sand density of 1.6 g cm^{-3}, this would give an SAR of around 0.1 mm yr^{-1} across the whole lake. Clearly this is not sufficient to bury pine pollen and thus it is likely that, excluding algal production, the majority of the SS in the upper sediment traps came from fresh Aeolian inputs. Note, the small annual input of sand is consistent with the sediment in the cores (Fig. 15) having a thick organic layer over the sand rather than being mostly sand.

5.2.2 Nitrogen and phosphorus

Water column nutrient data indicate that Lake Ototoa is deficient in phosphorus leading to phosphorus limitation of algal growth (i.e., the TN:TP ratio >>10:1). Although phosphorus inputs to the lake were low, this is more likely to be a function of the iron sand in the sediments binding the phosphorus than an over supply of nitrogen from the catchment.

[2] Although pine trees were planted in the early 1900s to stabilise the moving sand dunes, I could not find records of when the coastal Kanuka forest around Lake Ototoa was replaced with pine trees. Pine trees produce copious quantities of pollen which would bring a sudden increase in carbon to the lake. Pollen dating of sediment cores from the lake may shed further light on when this carbon input first occurred in the lake.

Nitrogen loads in the surface inflows and groundwater from the catchment were estimated to contribute up to 4 kg TN d^{-1} compared with sediment nutrient release rates of about 2.1 kg DIN d^{-1}. However, much of the DIN in the catchment inputs may be removed as the stream water and groundwater enter the lake through an almost continuous buffer zone of emergent wetland plants (e.g., Lusby et al. 1998). This is consistent with the relatively low TN concentrations in the lake which were typically about 0.3 g m^{-3} while inorganic nitrogen concentrations were near analytical detection levels

In terms of total nutrient inputs, the catchment inputs, excluding Aeolian inputs, were estimated to be about double the total nitrogen released from the sediment, while TP loads were of similar proportions from both catchment and sediments. These data show that external loads, including Aeolian inputs, were the major inputs nutrient to the lake. Biogeochemical processing of those nutrients through the sediments transforms the particulate N and P material into plant usable forms as DIN and DRP which are released into the hypolimnion with a time lag after the particulate input occurred.

5.3 Management strategies

As lake Ototoa is a dune lake with no surface outflow, there is no chance to flush nutrients from the lake under high rainfall conditions. Consequently, there will be a continuous accumulation of any nutrients entering the lake from the catchment. As the catchment provides the largest input of nutrients to the lake, a logical management strategy would be to implement policies that reduce those external nutrient loads to the lake.

Following the ARC lakes monitoring data review in 1999 (Gibbs et al. 1999), farmers around Lake Ototoa voluntarily excluded stock from direct access to the lake and there has been a change in land use from dairy to deer farming. The increase in mean annual water clarity since 1999 (Fig. 20) may, in part, be due to these changes in land use. These modified land use practices should continue to reduce the input of catchment derived nutrients to the lake and thus limit the amount of algae that can grow in the lake.

However, while the modified land use practices deal with nutrients from fertilizer and animal waste, the largest proportion of the nutrient load on the lake is from Aeolian inputs and these are likely to be a function of the amount of bare land exposed through land use practices e.g., farm tillage, dirt roads, clear-felling of production forest at harvest, as well as local climate in terms of rainfall and wind direction. Management strategies need to be implemented that reduce these sources of wind-erodable soil and thus the Aeolian inputs to the lake.

6 Conclusions

- Lake Ototoa has a high water quality despite developing an anoxic hypolimnion within 2 months after thermal stratification in spring. High water quality is indicated by high clarity, low nutrient concentrations and algal biomass, and the development of a deep chlorophyll *a* maxima during summer stratification.
- The lake is nutrient limited with phosphorus being the most likely nutrient to limit algal growth (TN:TP ratios >10:1). The cause of the P-limitation is likely to be associated with low DRP concentrations in the inputs and the high iron content in the sediments which can bind phosphate rendering it unavailable for immediate algal growth. Inorganic nutrients from the catchment, via the stream and ground water inflows, are also likely to be removed by an almost continuous buffer zone of emergent wetland plants around the lake edge before they reach the open waters of the lake. Internal cycling of nutrients from the sediments supplies the largest proportion of inorganic plant growth nutrients to the lake water column, but external inputs, especially Aeolian, contribute the greatest total nutrient loads to the lake.
- Thermal stratification produces two thermoclines which are a feature of this lake. The deep thermocline isolates the bottom waters and is fundamental to oxygen depletion in the hypolimnion. The shallow thermocline tilts and oscillates affecting the water clarity estimates. The water movement caused by these oscillations may influence release rates of nutrients and enhance sediment resuspension by turbulent erosion of the littoral lake bed.
- Sedimentation rates were variable with apparent high inputs of inorganic (sand) and organic material during windy periods. While internal algal production and sediment resuspension contribute to the vertical flux of particulate material, Aeolian inputs contribute a substantial proportion of new material to the lake. The Aeolian inputs of organic material, including pollen, are likely to enhance the sediment oxygen demand during decomposition and exacerbate the rapid loss of oxygen from the hypolimnion after thermal stratification in spring.
- This study found that, based on changes in hypolimnetic oxygen depletion rates and mean monthly water clarity, there has been a decline in lake water quality since 1969/70. Based on water clarity, the decline was likely to have been a "step-wise" change of <2 m between 1970 and 1988. Since 1990 there has been no net change in the mean monthly water clarity. Although small trends of increasing TN and TP concentrations were found from 1990 to 2006, these were at a level of <10% of the analytical precision and may not be real.

- Historically the change in water clarity was linked with wind (Green 1975). This study confirms that link, finding that temporal water clarity variability was most likely caused by Aeolian inputs of sand and dust rather than by algal proliferation stimulated by nutrient inputs. A statically significant positive relationship since 1994 between mean annual water clarity and annual rainfall ($p<<0.001$, $r^2 = 0.87$, $n = 10$) indicated that high rainfall years produce less suspended solids in the lake, presumably by damping down bare land, although higher lake levels may reduce wind-induced re-suspension of littoral sediments.

- The cause of the decrease in the average water clarity between 1970 and 1988 may correspond with a major switch in climate (ENSO and IPO) from predominantly La Niña (north-easterly winds) to El Niño (westerly winds) between 1970 and 1988. The change in water clarity may be attributable to a greater wind-induced stirring enhancing littoral sediment re-suspension or a higher Aeolian input of inorganic and organic material from external sources. A potential external source of organic material in spring could be pollen from the extensive pine forests growing on the sand-dunes to the west of the lake.
- A sudden decrease in water clarity around 1997/98 appears to have been caused by an event associated with the clear-felling of a stand of pine trees on the western shores of the lake. Exposure of bare sand during clear-felling of pine trees during harvest elsewhere on the western side of the lake since then is likely to be enhancing the Aeolian inputs to the lake and may be reducing the rate of recovery in lake water quality observed since 1999.
- Since 2000, voluntary changes by farmers in land use practices have included exclusion of stock from direct access to the lake and a switch from dairy to deer farming. The recovery of the lake water quality since the 1997/98 event, indicated by the increase in mean annual water clarity since 1999 may, in part, be due to these changes in land use.

7 Recommendations

The pre European landscape around Lake Ototoa was dominated by Kanuka forest and extensive sand dunes to the west of the lake. Pine trees were planted to stabilize the sand dunes, and there are now extensive pine forests on the western side of the lake. The effect of pine trees on the lake is largely unknown although elsewhere there have been concerns about pollen clouds from the mature trees in spring and soil erosion when the trees are harvested. Clear-felling leaves the soil bare for months to years and vulnerable to erosion by rainfall for up to 8 years.

Presently there is no production forest in the lake catchment and thus erosion by rainfall is unlikely to impact on Lake Ototoa, although it may have in the past. Aeolian inputs from wind erosion of bare soil from whatever source, and wind blown pollen from any plants, have the potential to impact on the water quality of the lake. The weight-of-evidence in the data collected in this study imply a link between the forestry activity in the catchment and the decline in lake water quality with a substantial decrease in lake water clarity during forest harvesting and a slow recovery as the sand dunes are stabilized once more by the newly planted forest.

While this implies an adverse relationship between pine forests and lake water quality, it should be remembered that it is better to have the pine trees protecting the land from wind erosion in the longer term, until a better alternative is found.

To resolve this issue and improve the knowledge of the lake and the processes driving the apparent decline in water quality, I recommend that sediment cores are taken at several locations in the lake including deep and intermediate depths to examine the lake history, assess sediment accumulation rates, and the rate of in-filling of Lake Ototoa. The cores should be examined for evidence of historic sedimentation events that could have occurred between 1970 and 1988 and around 1991 and 1997 to identify the cause of sudden changes in lake clarity at those times. The pollen record should also be examined to determine when pine pollen first appeared, and whether there are any indications of annual accumulations of sand and organic material with respect to the pine pollen and other pollen signatures. These data should provide the information linking water quality changes to changes in land use and allow management strategies to be developed that would reduce future impacts on the lake.

There may be other subtle affects associated with the switch between predominantly La Niña (North-easterly) and El Niño (Westerly) weather patterns in the 1970s. These include the possibility that the lake is more susceptible to sediment re-suspension by winds from the south-west quarter. I recommend that the relationship between wind strength and direction and water column suspensoids versus airborne deposition should be investigated.

The positive relationship between rainfall and water clarity may also be an indication that high lake levels can reduce wind-induced re-suspension of littoral sediments. However, there are no water level data for the lake to test this hypothesis. I recommend that a water level "staff gauge" be installed near the point of entry to the lake for the routine monitoring and that lake water level be added to the suite of parameters in the ARC Lake monitoring data base. I also recommend that consideration be given to installing a water level recorder with an optical back scatter (OBS) turbidity sensor for a period of at least 1 year to investigate the relationship between water clarity, water depth, and rainfall.

Farmer initiatives for reducing nutrient loads in the catchment are to be commended and should be encouraged.

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10 Appendix 1 – Historical data

10.1 Data from 3-5 February 1950

Extracted from Cunningham et al. (1953).

The lake was incorrectly called Lake Rototoa. The lake was described as a typical valley lake in Northland. In February 1950, the lake had no in-lake vegetation along the exposed western shores. There was much windblown sand entering the lake. There were moving sand-dunes and stabilization of the sand-dunes at the south-western end of the lake catchment had recently started. There were no exotic pine forests around the lake.

On 4 February 1950, the lake had a maximum depth of 29 m. It was not stratified, having been recently wind mixed, and the temperature was 23.5ºC down to 25 m. Surface and bottom oxygen concentrations were 9.0 g m^{-3} (110%) and 5.8 g m^{-3} (55%) respectively. Secchi depth was 9.0 m; ph was 6.2; silicate was 4 g m^{-3}; Chloride, DRP, NO_3-N, and NH_4-N were 58.2 g m^{-3}, 0.016 g m^{-3}, 0.2 g m^{-3}, and 0.06 g m^{-3}, respectively.

This report (Cunningham et al. 1953).also contains substantial phytoplankton, zooplankton, macrophyte and other information about Lake Ototoa and other New Zealand coastal dune lakes.

10.2 Data from 1969/70

Extracted from Green (1975).

The 1969/70 study found that Lake Ototoa was a warm monomictic lake which became thermally stratified in November, the metalimnion being between depths of 12 m and 16 m. Surface temperatures ranged between 10.2°C (in August) and 25.2°C (in late January), and bottom temperatures between 9.7°C and 17.5°C. The annual heat budget was calculated to be 642 354 KJ.m^{-2} (15 500 cal.cm^{-2}) and the work of the wind in distributing the heat income 1.730 KJ.m^{-2} (1766 g.cm.cm^{-2}). Secchi disc transparencies ranged between 5 m and 9.2 m (mean 7.07 m) and were greatest in the summer. There was a negative correlation between wind speed in the previous 5 days with water clarity in the lake, suggesting this was caused by windblown material from nearby dunes. Light transmission per metre [measured by photometer] was also high, ranging between 61% and 87%. Surface waters were normally supersaturated with oxygen, but during summer stratification oxygen concentrations in the bottom waters dropped to a minimum of 2.3 mg.$litre^{-1}$ producing a positive heterograde distribution of oxygen with depth. The oxygen deficit was 0.015 mg.cm^{-2}.day^{-1} and showed the lake to be oligotrophic. Mean surface pH was 7.82, and the ionic composition of the waters was similar to that of other small New Zealand and Australian dune lakes located near the sea. Compared with other New Zealand lakes PO_4-P concentrations (range 1.00-10.20 µg.litre^{-1}) were low and NO_3-N concentrations (range 0.12-0.60 mg.litre^{-1}) high

The physical data in this report show little change since that study. The major changes found in 2005/06 were that the lake developed an anoxic hypolimnion and the mean Secchi disc transparency was 33% lower at 4.75 m. Both phosphate and nitrate concentrations in the surface waters in 2006 were significantly less that in the 1969/70 study although maximum concentrations in the hypolimnion were of an similar order of magnitude.

10.3 Hypsographic data

Table No. A1

Hypsographic data for Lake Ototoa (from Green 1975).

Depth	Area of contour	Volume of stratum	
(m)	(m^2 x 10^6)	(m^3 x 10^6)	(% of total)
0	1.623	3.072	15.39
2	1.451	2.791	14.99
4	1.34	2.574	12.9
6	1.234	2.339	11.72
8	1.106	2.092	10.49
10	0.987	1.857	9.31
12	0.871	1.629	8.17
14	0.759	1.362	6.83
16	0.605	1.021	5.12
18	0.421	0.673	3.37
20	0.258	0.368	1.85
22	0.119	0.14	0.7
24	0.037	0.033	0.16
26	0.005		
Total volume		19.951	

11 Appendix 2 – Analytical comparison

11.1 Comparison between NIWA and WSL results

Table A2.1 presents a comparison of analytical data from water samples collected from the lake on 12 January 2006 and analysed by NIWA and Watercare Services Ltd (WSL) laboratories. Although the samples were not split as would be required for an inter-laboratory comparison, the samples were collected from the same location at the same time using the same sampling equipment but placed in sample bottles prepared by the individual laboratories.

Table A2.1

Comparison of selected nutrient data from Lake Ototoa water samples collected on 12 January 2006 as analysed by Watercare Services Limited (WSL) and NIWA. (WSL analyse the routine ARC monitoring samples). Column headings are from the ARC monitoring database with NIWA equivalent.

ARC name	Depth	SS	Chloro	Pm/f-arc	Ptot-arc	NH3-arc	NO3NO2	TKN-Titr
NIWA name	Depth	SS	Chl-*a*	DRP	TP	NH_4-N	NO_3-N	TN
	(m)	(g m^{-3})	(g m^{-3})	(g m^{-3})	(g m^{-3})	(g m^{-3})	(g m^{-3})	(g m^{-3})
Laboratory								
WSL	0	1.0	0.0012	0.015	0.027	0.011	0.007	0.200
	3	1.8	0.0025	0.012	0.022	0.019	0.006	0.200
	8	0.8	0.0027	0.014	0.019	0.014	0.025	0.200
	15	1.8	0.0029	0.010	0.018	0.025	0.013	0.200
	20	4.2	0.0007	0.010	0.017	0.138	0.005	0.200
	22	4.4	0.0017	0.010	0.018	0.189	0.006	0.200
NIWA	3	1.6	0.0030	0.001	0.011	0.003	0.001	0.286
	8	1.4	0.0025	0.001	0.007	0.004	0.001	0.286
	12	1.2	0.0035	0.001	0.008	0.002	0.001	0.269
	16	2.0	0.0015	0.001	0.008	0.042	0.001	0.278
	21	2.2	0.0015	0.001	0.009	0.045	0.001	0.270

11.2 Analytical concerns

11.2.1 Sample comparisons

The marked difference in results from the two laboratories for essentially the same water sample is of concern and indicates a potential problem with the ARC lakes monitoring programme data. The main concerns are the higher nutrient and suspended solids concentrations from the monitoring programme WSL analyses. For example, the NIWA results found no NO_3-N at any depth but the WSL results report significant levels. If the WSL NO_3-N results were correct, there should be no DRP [Pm/f-arc] as the phytoplankton would quickly use the DRP leaving the residual NO_3-N. Similarly for NH_4-N. DRP is present in very low levels and the lake is P-limited to phytoplankton growth. This is not consistent with the levels of DRP reported by WSL. Bottom water SS values from WSL were twice those from the NIWA samples.

11.2.2 Database concerns

Data errors noted by Gibbs et al. (1999) are still present in the database and these may also influence any trend analysis.

Areas of concern with the database include:

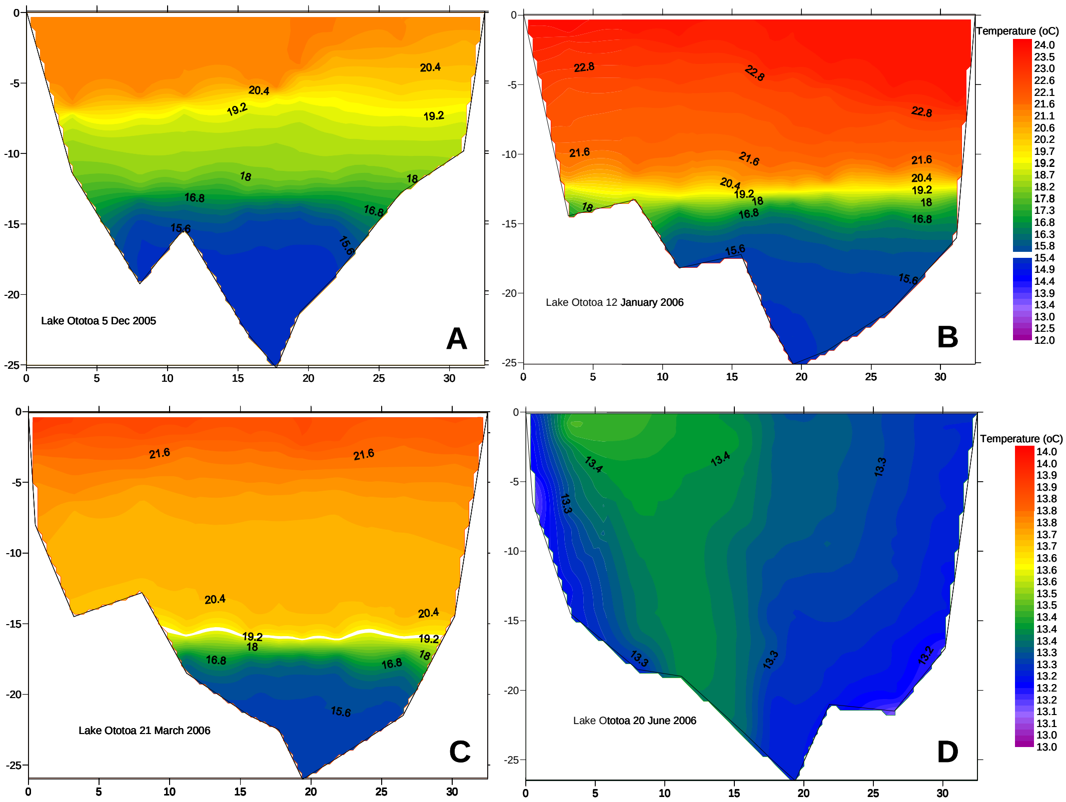
- The presence of data entry errors with occasionally high (suspect) values because of an incorrect decimal place or a typographical error. While most of these were obvious as being ecologically impossible for this lake, others were more subtle, being inconsistent with data before and after.
- Contamination. It has been found that lake water samples for NH_4-N preserved with sulphuric acid can be subject to contamination because the acid adsorbs NH_4-N from the air. The ARC NH_4-N water samples are preserved with acid.
- Incorrect sampling depths which did not provide the information expected. Evaluation of the Lake Ototoa data found that 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. As there were gradients in the nutrient and dissolved oxygen concentrations in the hypolimnion (e.g., NH_4-N, Fig. 14; DO, Fig. 8), even a small difference in the "bottom" depth of the samples collected before 2000 could result in a substantial difference in the concentrations measured.
- Analytical precision of some of the ARC lakes monitoring programme data changed from high to low in the early 1990s with detection and reporting levels well above the expected values for a high quality lake. Inorganic N and P concentrations reported to 0.01 g m^{-3} with a detection level of 0.01 g m^{-3} cannot be used to determine trends in the data where changes of 0.001 g m^{-3} may be ecologically significant.

12 Appendix 3 - Temperature

Contour plots of the temperature structure along the axis of the lake show the tilting of the upper thermocline in December 2005 (Fig. A3.1A) and January 2006 (Fig. A3.1B), and the deepening of the thermocline during summer. Winter mixing data show that the lake was essentially isothermal although at a finer resolution there appeared to be a slightly warmer plume in the centre of the lake (Fig. A3.1D)

Figure No. A3.1

Contour plots of the temperature structure of Lake Ototoa along the transect line from south end (LH side) to north end (RH side) on the 4 sampling occasions. Temperature data in plots A, B, and C use the key from plot B. Left hand axis on each plot is depth in m. Bottom axis of each graph is distance in 100m units from the south end of the lake (i.e., the lake is 3.25 km long). Differences in the bottom topography of each plot reflect the depth differences caused by small lateral movement around the sampling point.



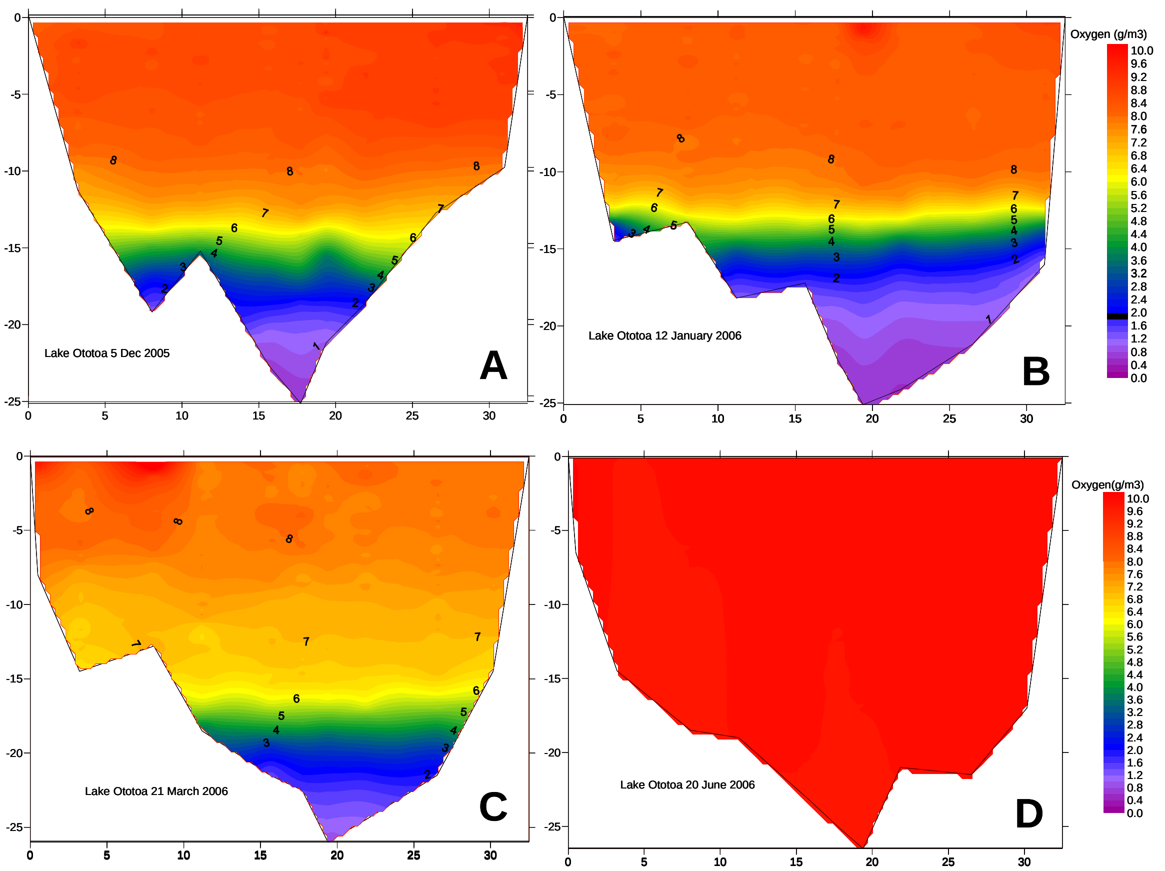
13 Appendix 4 – Oxygen

13.1 Oxygen distribution

Contoured plots of the oxygen data (Fig. A4.1) match the temperature plots although there was an apparent oxygen gradient below the thermocline on each occasion during the stratified period.

Figure No. A4-1

Contour plots of the dissolved oxygen distribution in Lake Ototoa along the transect line from south end (LH side) to north end (RH side) on the 4 sampling occasions. Left hand axis on each plot is depth in m. Bottom axis of each graph is distance in 100m units from the south end of the lake (i.e., the lake is 3.25 km long). Differences in the bottom topography of each plot reflect the depth differences caused by small lateral movement around the sampling point.

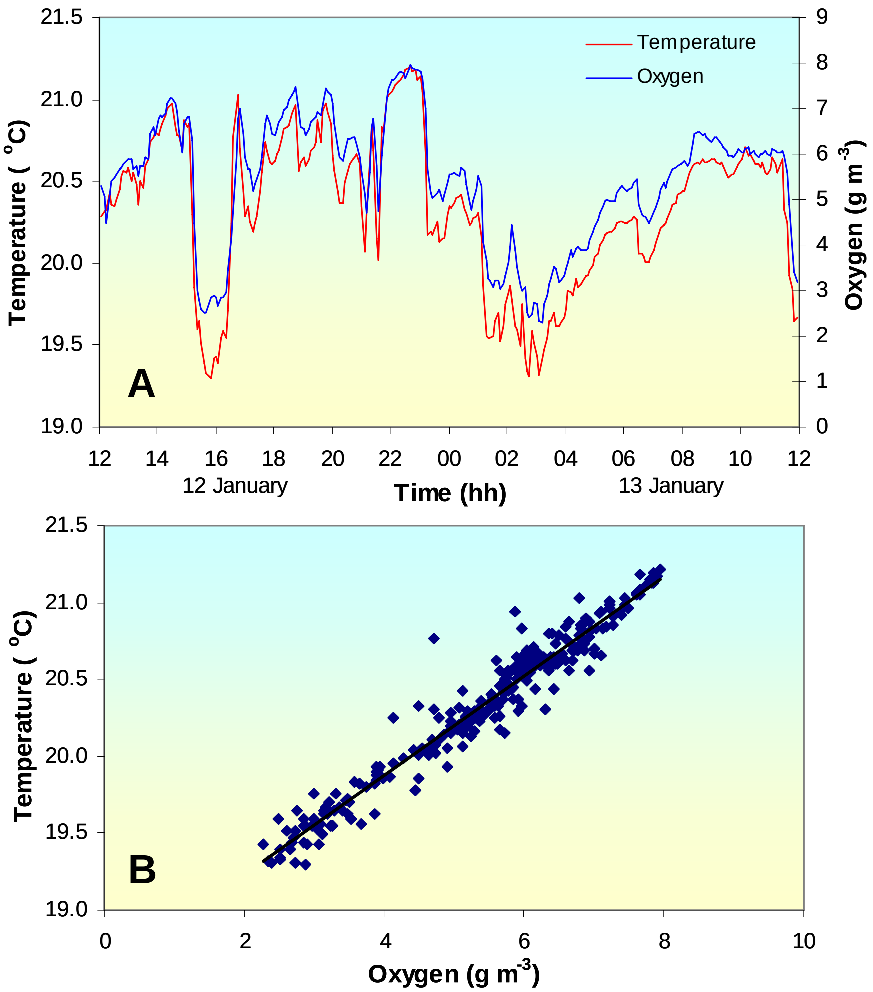


13.2 Turbulence and oxygen transport

Evidence of turbulence was seen in the temperature and oxygen data (Fig. A4.2) from a sensor mounted 0.2 m above the sediment on the outside of a benthic chamber deployed in 11 m water depth on 12 January 2006. The change in oxygen was directly correlated with temperature (r^2 = 0.9474) (Fig. A4.2B) which is consistent with the oxygen gradient across the thermocline at that time. The temperature rises as the thermocline moves down carrying well oxygenated epilimnetic water over the sensor (and sediments). As the thermocline moves up again, cooler oxygen-depleted hypolimnetic water is drawn over the sensor. From the temperature profiles on 12 January 2006 (e.g., Fig. 8), the 1.6 °C temperature change represents a vertical motion of the thermocline of 1.4 to 1.8 m.

Figure No. A4.2

A) Temperature and oxygen data from a logger mounted on a benthic chamber 0.2 m above the sediment in 11 m water on 12 January 2006. Data was recorded at 5 minute intervals. (B) Correlation between oxygen and temperature data (r^2 = 0.9474) consistent with the oxygen gradient across the thermocline on that day.



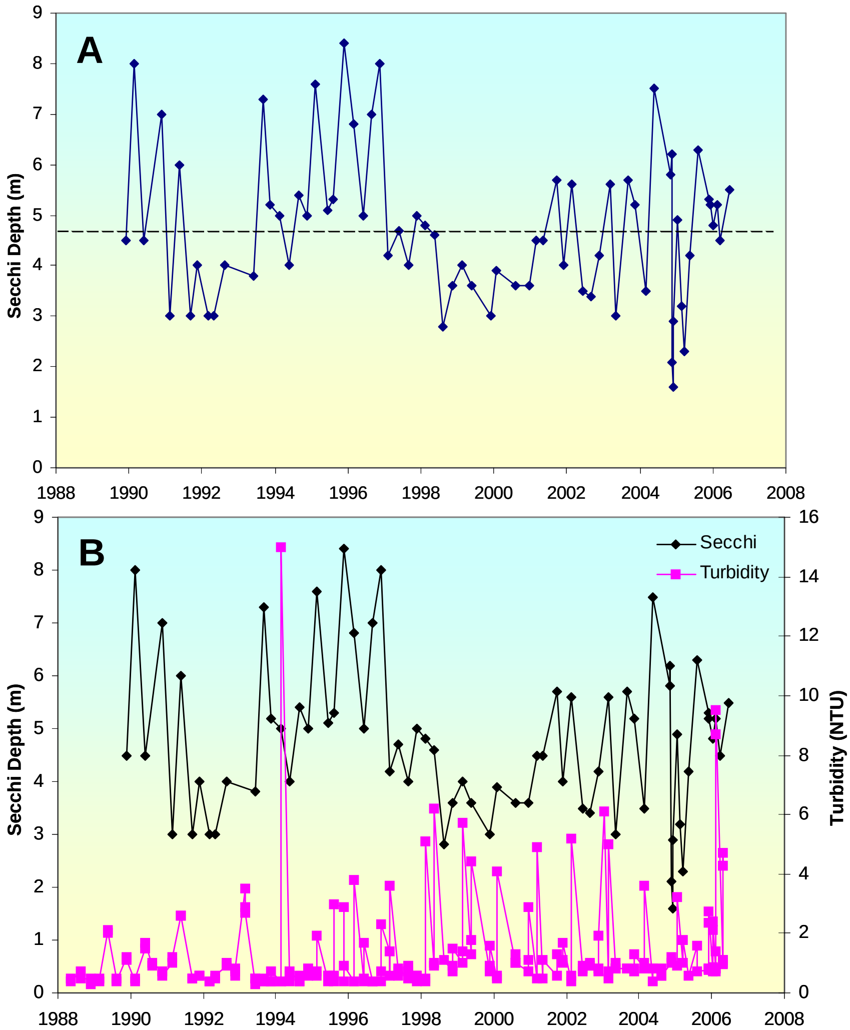
Vertical motions of this type are relatively common in lakes that thermally stratify and are often associated with seiches, which are waves on the density gradient of the thermocline. Seiches can cause the turbulent mixing across the thermocline and at the shore where the wave impinges on the lake bed (Spigel & Imberger 1987). Warmer oxygenated epilimnetic water would be entrained into the hypolimnion by this turbulence.

14 Appendix 5 - Water clarity

As Lake Ototoa water is essentially colourless, its water clarity must be a function of the amount of particulate matter in the water column. Secchi depth data are compared with turbidity (Fig. A5.1B), algal abundance (Fig A5.2A), and blue-green algal (cyanophyte) abundance (Fig. A5.2B).

Figure No. A5.1

Time-series plots of (A) water clarity as indicated by Secchi disc depth showing the natural variability around a mean value of 4.7 m (broken line) and (B) water clarity relative to turbidity in the lake. ARC monitoring data plus data from this study.

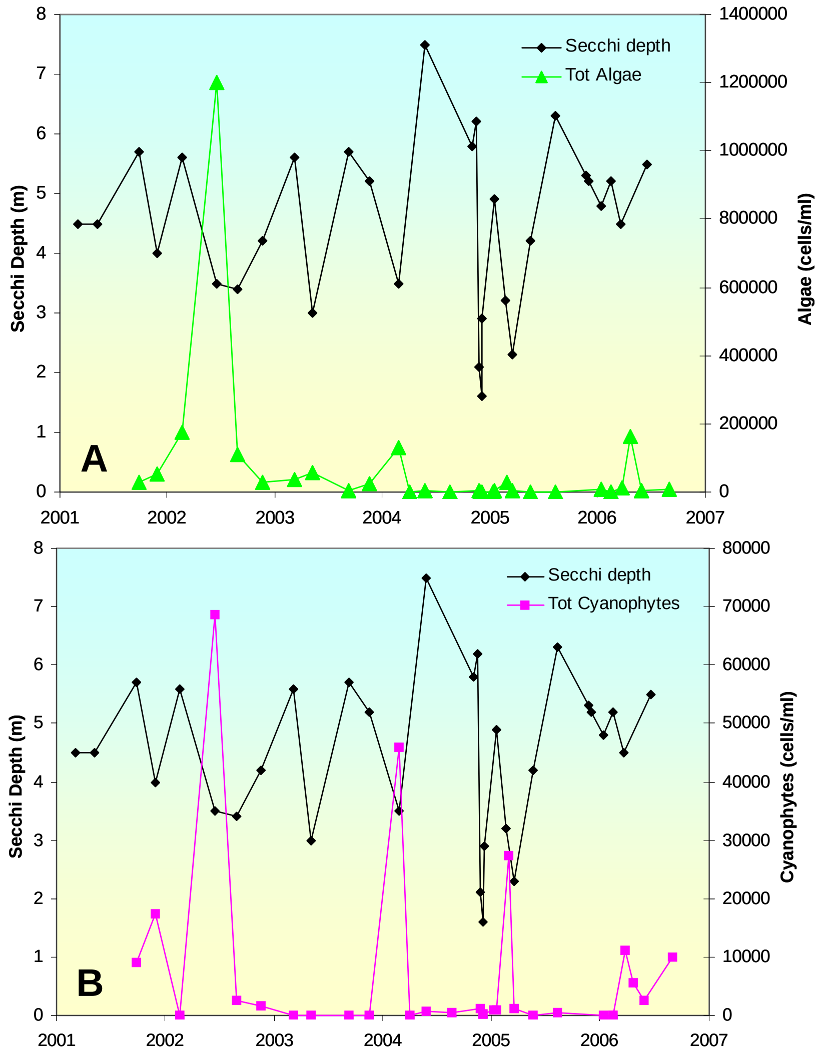


While water clarity should be inversely correlated with turbidity, there was no consistent or statistically significant relationship between Secchi disc depth and turbidity (Fig. A5.1B). Notwithstanding that, the background turbidity appears to be slightly higher after forest harvesting in 1997/98 than before, and there appear to be more turbidity spikes with generally higher levels of turbidity since 1998.

There was no correlation with total algae (Fig. A5.2A) and only a general correspondence with cyanophytes (Fig. A5.2B).

Figure No. 12

Time-series plots of (A) water clarity as indicated by Secchi disc depth relative to total algae (cells ml-) and (B) water clarity relative to total cyanophyte (cells ml-) in the lake since 2001. (ARC monitoring data).

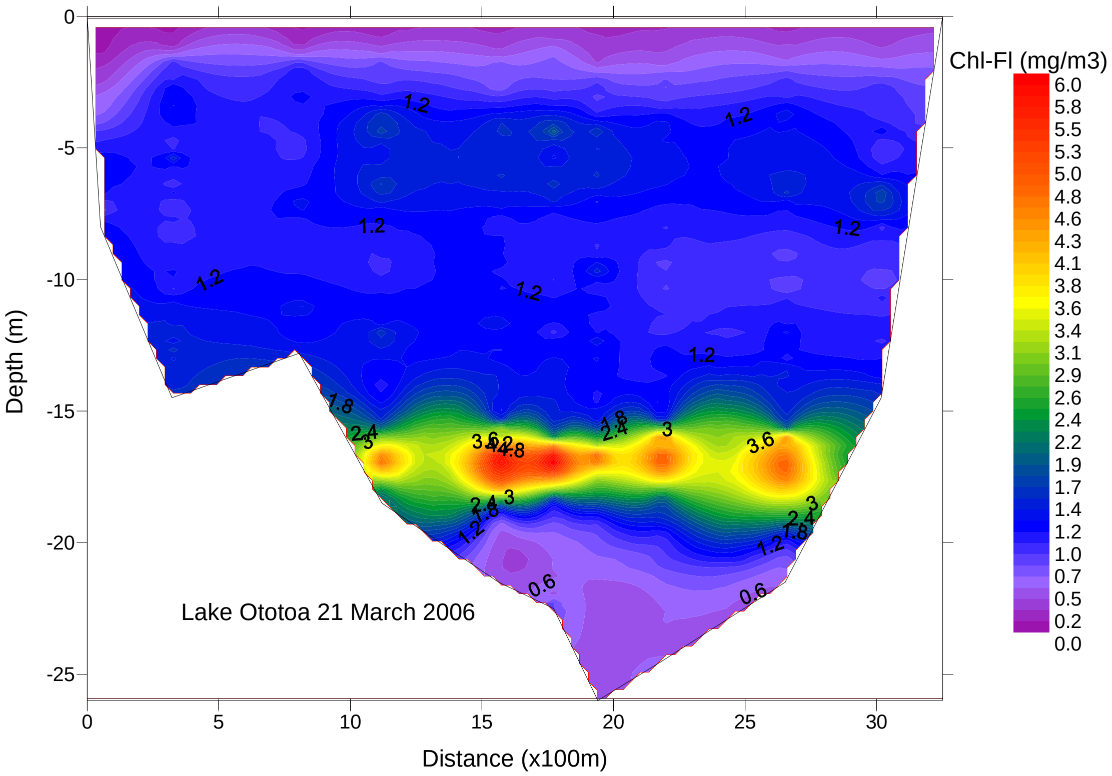


The apparent better correspondence between water clarity and total cyanophytes than the total algal cell numbers may reflect the ability of cyanophytes to accumulate at the surface under calm conditions and the tendency for monitoring to be undertaken on relatively calm days.

15 Appendix 6 – Chlorophyll

Figure No. A6.1

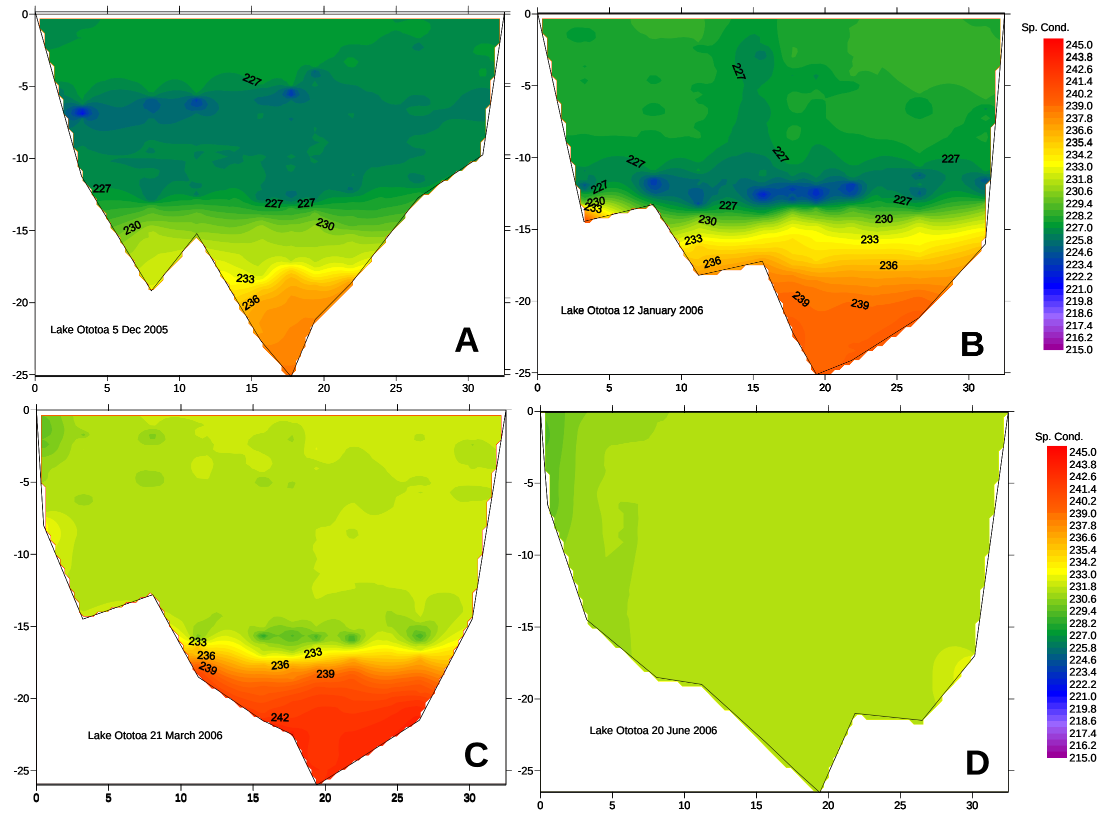
Contour plot of the algal biomass distribution in Lake Ototoa as indicated by chlorophyll fluorescence profiles on 21 March 2006, showing the deep chlorophyll maximum (DCM) along the axis of the lake. Bottom axis of the graph is distance in 100m units from the south end of the lake (i.e., the lake is 3.25 km long).



16 Appendix 7 - Specific conductance

Figure No. A7.1

Contour plots of the specific conductance along the transect in Lake Ototoa on the 4 sampling occasions. The gradual increase in specific conductance in the upper water column in sections A to C indicate an upwards diffusive flux across the thermocline. Section D shows that the nutrients and minerals associated with the increase in bottom water specific conductance have been dispersed throughout the whole lake after the lake mixed in autumn. Left hand axis on each plot is depth in m. Bottom axis of each graph is distance in 100m units from the south end of the lake (i.e., the lake is 3.25 km long). Differences in the bottom topography of each plot reflect the depth differences caused by small lateral movement around the sampling point.



The specific conductance in the epilimnion gradually increasing over summer is an indication of upwards diffusion of the minerals and gas released from the sediments.

17 Appendix 8 – Sedimentation

This section presents photo micrographs of the material caught in the sediment traps.

Figure No. A8.1

Photos of sediment on filters from the 8-m sediment traps on A) 5 December 2005, and B) 12 January 2006. Arrows indicate some examples of material in the traps. S = sediment and sand; D = dinoflagellate (*Peridinium sp.*); Di = diatom (*Aulacoseira sp.*); P = pollen (unknown).

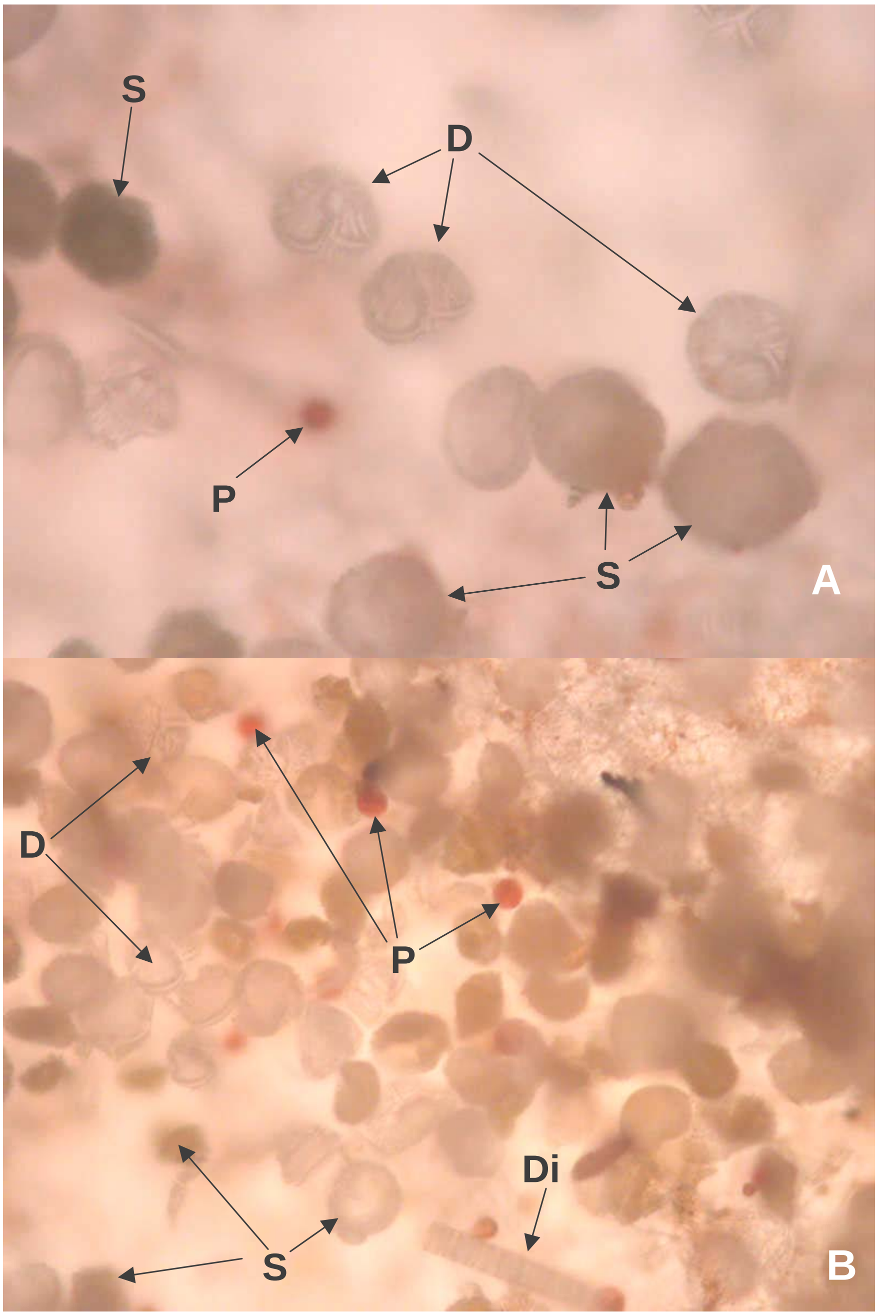
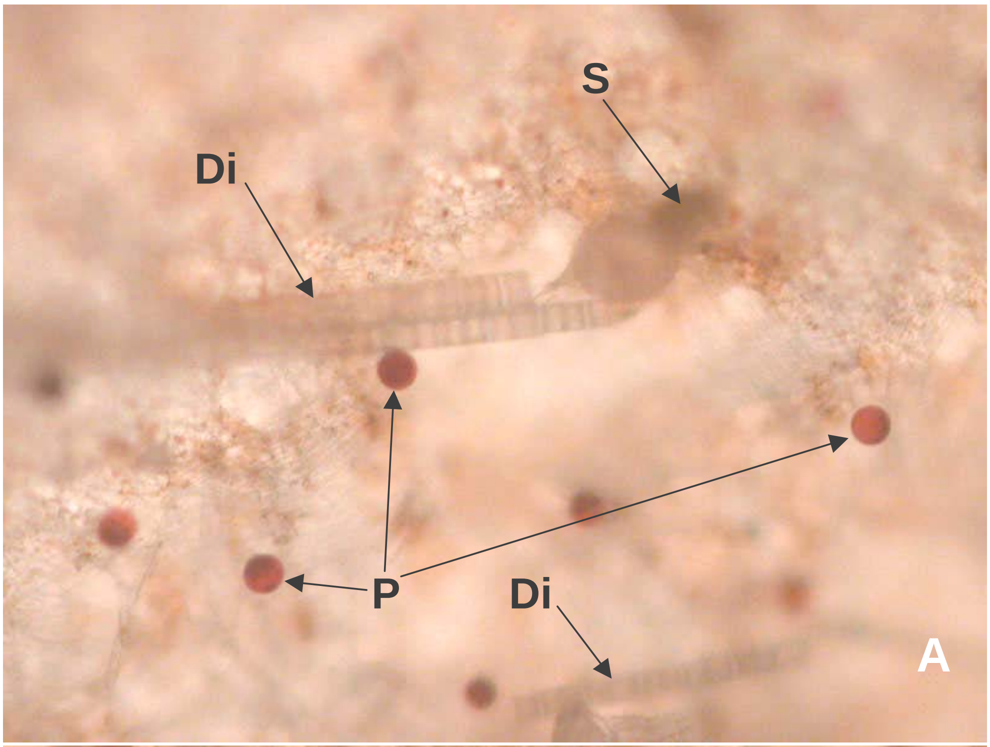


Fig No. A8.2

Photos of sediment on filters from the 8-m sediment traps on A) 21 March 2006, and B) 20 June 2006. Arrows indicate some examples of material in the traps. S = sediment and sand; D = dinoflagellate (*Ceratium sp.*.); Di = diatom (*Aulacoseira sp.*); P = pollen (unknown). Picture B) Di also include *Fragilaria crotonensis* (a comb-like structure)



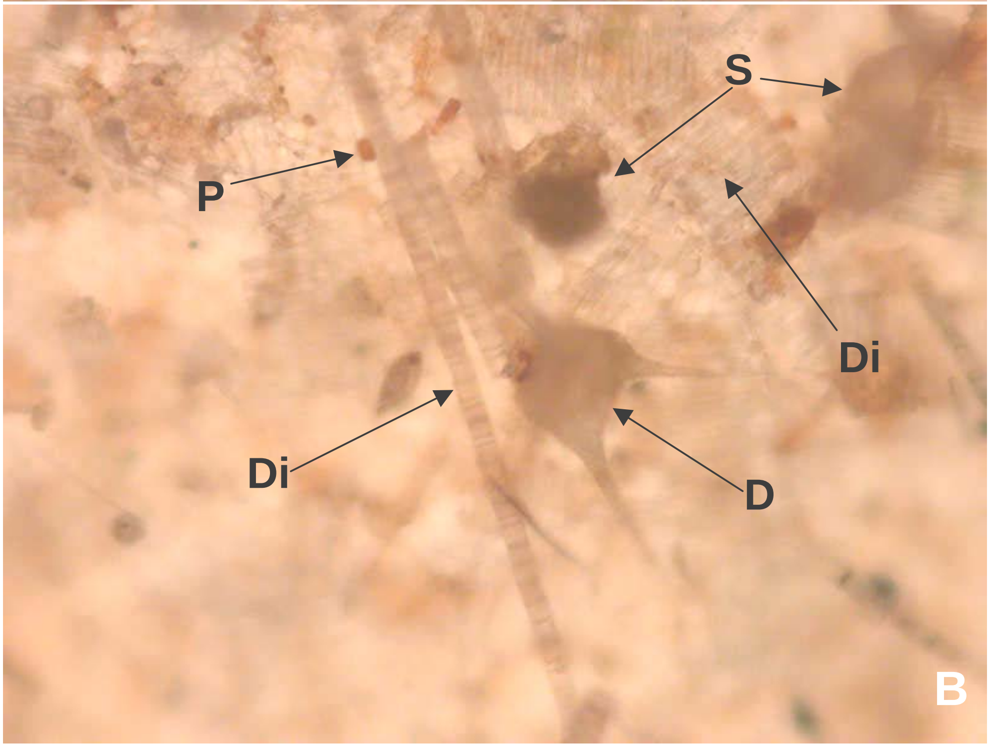


Fig No. A8.3

Photos of sediment on filters from the 8-m sediment traps on 20 June 2006 showing the high proportion of large lumps of sediment plus sand. Arrows indicate some examples of material in the traps. S = sediment and sand; Sa = sand; D = dinoflagellate (*Peridinium sp.*); Di = diatom (*Aulacoseira sp.*); P = pollen (unknown).