RESULTS OF MONITORING NEW ZEALAND LAKES, 1992 - 1996

Volume 2 - Commentary on Results

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N M Burns
J C Rutherford

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National Institute of Water & Atmospheric Research Ltd
PO Box 11-115, Hamilton
New Zealand
Tel: 07 856 7026
Fax: 07 856 0151

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ABBREVIATIONS USED IN THIS REPORT

Chla	Chlorophyll *a*
CTS values	Change of trophic state values
DO	Dissolved oxygen
DRP	Dissolved reactive phosphorus
EC	Electrical conductivity
HVOD	Hypolimnetic volumetric oxygen depletion rate
ISS	Inorganic suspended solids
LD	Lake depth
LMP	New Zealand lake monitoring program
NH_4	Ammonia
NO_3	Nitrate
Opacity	Inverse of secchi depth values (1/SD)
PAC	Percent annual change
OSS	Organic suspended solids
Pdiff	Total phosphorus concentrations minus dissolved reactive phosphorus concentrations
SD	Secchi depth
s.l.	significance level
TLI	Trophic Level Index
TLx	Trophic level for a variable
TN	Total nitrogen
TON	Total organic nitrogen
TP	Total phosphorus
T/DO profiles	Temperature and dissolved oxygen depth profiles
TSS	Total suspended solids

CHAPTER 1

1.0 MONITORING AND DATA ANALYSIS PROCEDURES USED IN THE NEW ZEALAND LAKES WATER QUALITY MONITORING PROGRAMME

Sampling of lakes commenced in February 1992 so that all procedures could be optimised by September 1992. September is the month when the lakes are undergoing little seasonal change, having been isothermal and well mixed for a few months prior to September. The data on each lake is thus tabulated annually on a September to September basis to the extent that the data allows. This report presents summaries of data collected from February 1992 to September 1992 and then from October to September of the following years.

1.1 Sampling Design

The main concepts implemented in the Lakes Monitoring Program design were that:

1. All analyses were carried out by the same laboratory using the same analytical techniques, so that small changes in concentrations were meaningful, and not the result of differing analytical capability between laboratories,
2. A minimum of two stations were selected for each lake, preferably at the deepest sites in the lake with the maximum possible distance between the sites,
3. Samples were taken monthly except in some lakes where sampling in July was omitted.
4. Data were collected on major indicators of eutrophication. The secchi disk depth was read on station and samples taken for nutrient, Chlorophyll *a* concentration and algal species determination,
5. Depth-Temperature-Oxygen (DTO) profiles to the lake bottom were taken at each station with carefully calibrated probes. This enabled hypolimnetic oxygen depletion rates to be calculated and the major mixing processes in the lake to be determined,
6. The downward mixing of oxygen in the lake associated with weather disturbances was calculated by using the DTO information. This data permitted determination of both the true and observed volumetric hypolimnetic oxygen depletion rates (VHOD) in stratified lakes using the methods outlined in Burns (1995),
7. Since VHOD cannot be measured in shallow lakes, suspended sediment concentrations were measured in them to obtain an idea of the magnitude of mixing events resulting from weather disturbances prior to sampling.

1.2 Sampling Details

After temperature and dissolved oxygen (DO) profiling had been carried out at a lake station, the first decision made was whether or not the lake was stratified. If it was, the depths of the bottom of the epilimnion and top of the hypolimnion were immediately determined. The equipment used to obtain the DTO profiles was a YSI 5739 probe with stirrer, and specially spliced cables where the lake depth was greater than the maximum commercially available 75m; the DO meter was a YSI Model 58 which gave a direct digital read-out of DO concentration and temperature.

Algal samples were subsampled from the mixed epilimnion sample taken at each visit to a sampling station. The samples collected during each year from each lake were mixed into a single sample which was analysed. Collection of algal samples commenced in December 1992.

Isothermal lakes

If a lake was not stratified, the sampling protocol was straightforward. Samples were collected at 1/4 and 3/4 of the maximum depth using a van Dorn bottle. At the upper sampling point, three 2.2 litre samples were collected, and then subsampled into a one litre bottle for nutrient analysis, a 100ml algal sample, and a five litre bottle (for filtering on shore for subsequent chlorophyll *a* analysis). A single van Dorn sample was collected at the lower sampling point from which a one litre bottle was filled: this was sent for nutrient analysis. This lower sampling point was changed if the bottom waters were anoxic. The rule-of-thumb, operational definition for anoxia was a reading less than 0.3 mg/l dissolved oxygen; in part to account for possible probe errors in such low saturation waters. The lower sample was then taken in the mid-point of the anoxic layer. Figure 1.1(a) in Volume 3 contains the above strategy in diagrammatic form.

Stratified lakes

Epilimnion sampling

Light energy provides the driving force for lake ecosystems, therefore water was sampled from the photic zone. A rough estimate of the photic depth (Z_{phot}) was obtained from the Secchi disc depth (SD) using published relationships. From the known character of the water, a list of multipliers (*K* values) has been produced from Davies-Colley and Vant (1988) to obtain an appropriate maximum sampling depth (Z_{samp}) from the Secchi disc depth. The *K* value was only established once for each lake.

The photic depth in a clear or relatively small lake may be greater than the upper mixed depth (Z_{mix}, ≅ epilimnetic depth) for a period in mid-summer. This combination of optical and thermal structure can be associated with a deep chlorophyll *a* maximum. More importantly in the present context, a relatively thin turbid layer of detritus is often present near the thermocline. This could be sampled, and consequently affect determinants such as turbidity, nutrients and chlorophyll, if depth integrated sampling were performed over the photic zone as a whole. Therefore when $Z_{mix} \leq Z_{phot}$, sampling was carried out only in the mixed layer (Z_{mix}).

In practice, the decision was that only the top 80% of the mixed layer depth (Z_{mix}) or the photic depth (Z_{phot}), whichever was the smaller, was sampled. Erring on the lower side of the estimated depth to be sampled (by 20%) minimised the risk of sampling too deep and perhaps biasing the sample. This was built into the *K* values referred to earlier.

Because of possible layering in the epilimnion, four 2.2 litre samples are taken using a van Dorn bottle, one just below the surface, one at the depth identified as above, and two others at intermediate points in the water column which were then pooled (Figure 1.1b). They were subsequently subsampled into a one litre bottle, a 100ml pottle and a five litre bottle. The chlorophyll *a* samples were filtered in duplicate on shore from the 5 litre sample.

Hypolimnion sampling

It would have been desirable to take a number of samples from the different depths in the hypolimnion for bulking, as in the epilimnion, but this was not possible without substantially increasing the time on station. Since the sampling bottle was hand lowered and retrieved, a sample from 60m took much longer and was more tiring to retrieve than one from 10m. Also, there was less reason to have four sampling points in the hypolimnion because the possibility of layering of particulate matter is not usually significant in this zone. Chlorophyll *a* concentration was not measured in hypolimnion samples because it is usually very low.

Samples were taken (2.2 litre van Dorn bottle) at 1/3 and 2/3 of the depth between the top of the hypolimnion and the lake bottom (Figure 1.1b). These were mixed and a single one litre subsample taken for nutrient analysis. However, if there was a deoxygenated zone (i.e., less than 0.3 mg/l DO) then the lower sample was taken in the middle of this zone, and the two samples are not mixed; a one litre subsample was taken for nutrient analysis from each separate sample.

A reason for sampling the anoxic waters separately from the oxygenated waters was to determine whether high concentrations of nutrients were present in these waters. A major effect of anoxia is the dramatic increase in the release rate of the nutrients, ammonium and soluble reactive phosphate, as well as iron, manganese and other minerals from the sediments to the water. The occurrence of high concentrations of these compounds in anoxic waters is often a truer indication of anoxic conditions than an oxygen probe measurement of, say, 0.5% saturation, because the reliability of probes decreases near the zero DO concentration point.

Worked example

By way of example, sampling depths were calculated for an actual run on Auckland's Lake Pupuke as follows:

The Secchi disc depth was 5.28m, from which our initial estimate of the maximum epilimnion sampling depth (z_{samp}) was 2.6 x 5.28 (where K = 2.6) = <u>13.7m</u>. This is the calculation for the *estimated depth of the photic zone*.

The epilimnion is defined as being the upper mixed layer and this concept is used in estimating its thickness. From the temperature profile (Fig. 1.2), the bottom of the epilimnion was estimated to be at 9.5m, from which we obtained 0.8 x 9.5 = <u>7.6m</u> for the maximum epilimnion sampling depth.

The shallower of the two underlined values for the maximum epilimnion sampling depth was selected, i.e., 7.6m. Therefore samples were taken at 0.25m (sub-surface), 2.5m, 5.1m and 7.6m. These samples were pooled prior to sub-sampling.

From the temperature profile (Fig. 1.2), the hypolimnion commenced at about 25m. The lake bottom was at 59m. Thus the hypolimnion sampling depths would have been at 36m and 48m. However, deoxygenation (i.e., less than 0.3mg/l or 3% saturation by the operational definition) commenced at about 39m so our lower sample (which smelt distinctly of H_2S) was taken at 49m. In this case, the two samples were analysed separately for nutrient concentrations.

Samples were not taken from the thermocline because this is a zone of the lake where concentrations can vary markedly with depth. In particular, this monitoring program was based in assessing change in the epilimnion and isothermal water masses and thermocline concentrations had little relevance to the results obtained.

1.3 Field sheet

All the above information was contained in a comprehensive field sheet (Fig. 1.3). The field sheet is basically a flow sheet of things that field staff did on the water and provided considerable assistance with decision making. It was kept as simple as possible but clarity was not compromised for brevity. The field sheet also had space for the entry of calibration data for the Temperature/DO Meter. Since changes in the temperature or DO in the hypolimnion can be very small, it is essential that the meter was kept accurately calibrated.

1.4 Determinands

The determinands chosen reflected the objectives of the programme. Table 1.1 was drawn up with this in mind. It also indicated where the determinands were measured and why they were proposed. Table 1.2 gives details on the analytical methods used. The variables considered in the Lake Managers Handbook (Vant 1987) to be sensitive indicators in the change in lake trophic state are Chlorophyll *a*, Secchi depth, total phosphorus and nitrogen, hypolimnetic oxygen depletion rate, and phytoplankton species and biomass. The results reported on here in subsequent chapters have confirmed this assessment for all variables except phytoplankton species and biomass.

1.5 Phytoplankton Analysis

Over each reported sampling period of approximately one year, a composite phytoplankton sample was compiled from monthly samples, preserved in Lugols iodine and examined for phytoplankton composition. Five to 100 mls of each composite sample was settled before counting at x 100 - 600 magnification (Lietz Diavert inverted microscope). Counts of a minimum of 300 cells were conducted and biolvolumes were calculated using dimensions and approximated geometric shape (Chang 1988).

1.6 Data Processing

The water quality and profile data collected on the various lakes have not been included in this report because of their large volume but are available as outlined below. Annual averages of the water quality data for each lake are included in Volume 3 - Data and Results.

The data have been placed in two data archives at NIWA, Hamilton. The first is the Profiles Archive where the temperature/oxygen depth profile data is archived by lake. Table 1.3 is an example of this data stored in the archive on Lake Pupuke. The second archive is the Water Quality Archive where the water quality data is stored by lake and Table 1.4 is an example of this data. Both the water quality and profiles data is stored on a CD-ROM Archive No. H-1998-004-A-1 and may be obtained by contacting the Information Technology Officer, NIWA Hamilton, P O Box 11-115, Hamilton, New Zealand.

1.7 Methods of Data Analysis

The prime objective of the data analysis is to detect a significant change in any parameter with time. This has been done with the variables which are not strongly related to trophic state by plotting them simply as a function of time and fitting a straight line to the data to determine whether there is a significant change with time. However, the data on the trophic state variables, namely chlorophyll *a* (Chla), Secchi depth (SD), total phosphorus (TP) and total nitrogen (TN), has been deseasonalized before fitting a trend line so as to increase the sensitivity of the trend detection procedure as described below.

If there are three or more years of data available for a lake, it is possible to carry out a valid deseasonalising procedure on the data. Temperature provides a good example of the data analysis procedures used and reported on here because the change of temperature of the water of the lake during the year is relatively large and similar from year to year.

Fig. 1.4A shows the epilimnetic temperatures which have been observed during the 5 years of monitoring, plotted only as a function of the time of year of collection with no regard for the year of collection. The curve shown in Fig. 1.4A is sinusoidal in nature but is a polynomial curve fitted to this data and represents the annualised pattern of temperature change. The reason for the use of a polynomial curvefit is that many of the annualised patterns displayed by the nutrient, Chlorophyll and Secchi depth data could not easily be approximated by sine curves. The annualised temperature for each day of the year can be calculated from the curve shown. Next, an observed temperature for a day is noted and the annualised value for that day of the year is subtracted from the observed data to yield a residual value for that particular day. The residual value for a day is in effect, the deseasonalised value for that particular day. The observed and residual data are plotted against time as shown in Fig. 1.4B and straight line plots are fitted to the data using ordinary least square regressions. A p-value is then calculated for the line fitted to the data. A low p-value means that there is a low probability that the fit of the line is attributable to chance. In other words, a low p-value means that there is a low possibility of observing a trend at least as large as the value calculated when there is no trend in the data. Since the units along the x-axis in Fig. 1.4B are years, the slope of the line designates the change per year in the variable and the p-value gives the smallest significance level that allows the null hypothesis of no trend to be rejected. The equation for the residual straight line has a slope of 0.306 indicating that the temperature of Lake Rotoroa increased at 0.306°C per year. For the line fitted to the residual data in Fig. 1.4B with a p-value <0.01, there is a less than 1% chance of observing a slope as large as 0.306 °C yr^{-1} when there is no trend in the data, whereas for the line fitted to the observed data there is a greater than 5% chance of observing a slope as large as 0.494 °C yr^{-1} when there is no trend in the data. The variability removed from the data by the deseasonalising procedure enables trends with time to be determined with more confidence.

Residuals have been calculated and straight lines plotted for both residuals and observed data for lake depth and temperature and the four variables which are the most informative about trophic state; namely, chlorophyll *a* (Chla), Secchi depth (SD), total phosphorus (TP), and total nitrogen (TN).

It should be noted that lower p-values are obtained with a higher number of samples. Thus the number of samples taken in a trend detection case needs to be kept in mind because low p-values can easily be obtained in cases where many samples have been taken, even with relatively low correlation coefficients. The number of samples taken from each lake has been mentioned for this reason. The significance level for establishing that a trend has been detected has been 5% ($p \leq 0.05$) for this study where generally between 150 to 200 epilimnion or isothermal samples have been taken from each lake.

1.8 Interpretation of Results

While it is relatively easy to take samples, analyse them and detect trends of change with time, it is more difficult to determine whether the observed changes have indicated a change in the trophic state of a lake. The “Lake Managers Handbook” (Vant 1987) provides a lead in interpreting monitoring results by identifying Chla, SD, TP, TN and hypolimnetic HVOD as the key variables in assessing the trophic state of a lake. Phytoplankton species are also identified as being important in this regard. However, lack of funding did not permit analysis of enough phytoplankton samples for time trend analysis and only the first five variables listed above have been used in determining whether a change of trophic state has occurred.

1.8.1 Change of Trophic State Values

Change of trophic state values (CTS) were used in a study by Burns et al. (1997a) investigating possible change in the trophic state of some Rotorua District lakes. The same technique has been used here to assign CTS values to each time trend analysis of Chla, SD, TP or TN data of three or more years of duration according to the following relationship:

p-value > 0.05	=	CTS value of 0
p-value of 0.05 to 0.02	=	CTS value +1 or -1
p-value of 0.0199 to 0.01	=	CTS value of +2 or -2
p-value < 0.01	=	CTS value of +3 or -3

Changes which indicate increased eutrophication are assigned positive values and changes indicating decreased eutrophication are given negative values.

HVOD rates were calculated for stratified lakes but these rates had CTS values assigned on a different basis to the above four trophic state variables. The reason for this is that four years of data on a lake would yield between 100 and 200 values for Chla, SD, TP or TN but only four HVOD rates. Since p-values calculated from smaller numbers of samples are generally higher the CTS values were assigned to p-values from HVOD rates on the following basis:

p-value > 0.20	=	CTS value of 0
p-value 0.20 to 0.10	=	CTS value +1 or -1
p-value of 0.099 to 0.01	=	CTS value +2 or -2
p-value < 0.01	=	CTS value +3 or -3

Judgement has to be used in assigning CTS values to p-values because there is no direct relationship of p-values to sample numbers, only a general trend. This matter will always be of some concern because as monitoring programmes exist for longer periods, the number of samples will become higher, giving relatively low p-values. This trend will have to be considered otherwise it will lead to erroneous conclusions that most of the relationships investigated were statistically significant.

The particular power of using a CTS value is that it expresses the results derived from the different variables in the form of a common unit, CTS units. This means that the results from 4 variables (shallow lakes) or 5 variables (stratified lakes) can be combined into a single average CTS value plus standard error and p-value for each lake. Table 1.5 shows the CTS values obtained for each lake as well as their averages, standard errors and p-values. In this situation the p-value of each CTS average gives the probability that such a calculated average value could be obtained by chance if its value was in fact zero. The CTS values do not give any idea of the magnitude of the change which occurred in a lake, but give a clear indication of the probability of change in individual variables in a lake and of the probability of change in the lake as a whole.

1.8.2 Percent Annual Change (PAC) values

Another method of determining whether a lake has changed or not, is to calculate the percent annual change (PAC) in its trophic state variables. Again using Lake Rotoroa data for an example, Chla data for this lake (Fig. 4.2B) was seen to change significantly ($p<0.02$) at the rate of -1.72 mg m^{-3} per year. Since the average concentration of Chla during the monitoring period was 16.3 mg m^{-3} (Table 4.1), the PAC value of -10.4% was obtained by dividing this value into the annual change per year value.

PAC values also express the significant changes observed in all the variables in the same units, namely percent change per year thus enabling the results from the different variables in a lake to be added and averaged to give a single result for a lake. The average PAC value gives some idea of the magnitude of change which has occurred. Table 1.6 shows the PAC values obtained for each lake as well as their averages, standard errors and p-values. These p-values give the probability that that the calculated PAC average value could be obtained by chance, if in fact its value was zero.

1.9 Lakes Trophic Level Index (TLI)

W. N. Vant published a list of the 4 major lake types found in New Zealand in Table 5.5 of Davies-Colley et al. (1993), together with the values of the trophic state variables associated with each of these lake types, as shown here in Table 1.7. Vant's scheme was examined as a possible base for a trophic level scheme for NZ lakes but was not chosen because it did not contain enough lake types. It is not reasonable to consider lakes with Chla concentrations between 5 and 30 mg m^{-3} to be similar in nature; there should be at least two classes of lakes in this range of chlorophyll concentration. Also, there are at least two classes of oligotrophic lakes with Chla concentrations below 2.0 mg m^{-3}.

Carlson (1977) and Chapra and Dobson (1981) both proposed trophic state index schemes, shown in outlined in Table 1.8, but neither of these schemes seems appropriate to NZ lake conditions. Carlson's scheme is based on Secchi depth with the SD of each new level being half that of the previous level and results in large increases in the Chla concentrations in each of the eutrophic levels. In other words, Carlson's scheme is too coarse in its higher trophic levels for NZ conditions. Chapra and Dobson's scheme is based on Great Lakes data, proposing 5 levels for the mesotrophic range. This is too fine a scale for NZ lake conditions.

As a result of the above considerations, a Trophic Level Index (TLI) scheme is proposed here, which is suitable for a wide range of NZ conditions. It is based on the Vant scheme but has one more level of lake type for the Chla range of 5 to 30 mgm^{-3} than does Vant. It includes TN in the scheme, although Carlson (1977) and Chapra and Dobson (1981) did not, because many NZ lakes are nitrogen limited. After examining different types of relationships between variables, it was found that log(Chla) vs log(SD, TP, TN) produced the most stable relationships. Further, annual average values for each lake for each year are used for calculating equivalent trophic level values for Chla (TLc), SD (TLs), TP (TLp), and TN (TLn). Annual averages are in effect deseasonalised values and are thus fairly stable values.

The equation which best relates the 3 designated trophic levels to the values of 2.0, 5.0, 30.0 mg m^{-3} of Chla is;

$$TLc = 2.22 + 2.54 \log(Chla) \qquad \text{eqn. (1)}$$

This is shown in Fig. 1.5. Equation 1 can transform all annual average Chla values into equivalent Chla tropic levels, i.e. TLc values. Seventy five annual averages each for SD, TP, TN, from the 24 LMP lakes plus Lake Taupo from 1995 to 1997 (pers. comm. Max Gibbs ,NIWA and Nick Edgar, Environment Waikato) were plotted against TLc as shown in Fig. 1.6. the values for SD were modified as discussed by Chapra and Dobson (1981) to allow for the absorption of light by water. Crater Lake, one of the worlds clearest lakes has a SD of 40m so this value was used. The assumption made here is that for any set of annual average values for one year from a specific lake,

$$TLc = TLs = TLp = TLn \qquad \text{eqn. (2)}$$

thus enabling the equations shown in Fig. 1.6 to be obtained. These equations are;

$$TLs = 5.10 + 2.27 \log(1/SD - 1/40) \qquad \text{eqn. (3)}$$
$$TLp = 0.218 + 2.92 \log(TP) \qquad \text{eqn. (4)}$$
$$TLn = -3.61 + 3.01 \log(TN) \qquad \text{eqn. (5)}$$

The assumption (eqn. 2) is not upheld in each individual case and the distance of the points from the regression lines in Fig. 1.6 is a measure of the correctness of this assumption. Nevertheless, the average values of TLc, TLs, TLp, and TLn (TLx) calculated from all the values of these parameters was the same in each case and equalled 3.66 TLI units. The TLI scheme developed using the above stated principles and equations 1,3,4 and 5, is illustrated in detail in Table 1.9. In addition, values of the trophic level variables can be calculated for TLI levels of 8 or higher.

The annual average values used for calculating the TLx values are not exactly the same as the average values shown in the tables of data in the chapters on each lake. Data collection commenced in February 1992 and ceased in June 1996 so the averages calculated for each September to September year do not always derive from a full years data. However, the annual average data used in calculating TLx and TLI values are from periods of strictly one year. The results of the TLx and TLI calculations for all the lakes in the study are shown in Table 1.10.

1.10 Determination of Change or Stability in Trophic Level

The determination of whether a lake has changed with time is essentially done from the results obtained for the relative indicators of change, the PAC and CTS averages. The TLI trend with time can be very informative if the trophic state variables show small but similar trends with time as is the case with Lake Okareka, but can be misleading if only one variable shows a large degree of change such as Chla in Lake Maratoto (Table 1.10). As a result of this instability, the CTS and PAC values are used to confirm or reject the observed TLI time trends.

The decision on whether a lake has changed over time is made by examining the mean of the CTS and PAC p-values (see Table 1.11). If the mean p-value is derived from 2 p-values which are essentially both in the same range of one of the ranges shown in the table below,

Mean p-value range	Interpretation
< 0.1	Definite Change
0.1 - 0.2	Probable Change
0.2 - 0.3	Possible Change
> 0.3	No Change

then a confident assessment can be made as to the likelihood of change having occurred. The TLI trend value (Table 1.11) gives an indication of the magnitude of change which may be occurring in lake. This calculated rate of change is confirmed or rejected by whether it is in agreement or not with the degree of change indicated by the PAC and CTS averages and their p-values. There has to be good consistency between all these values if a firm assessment of change, or stability, in the level of a lake with time is to be made.

1.11 Contents of the Different Volumes

The data collected on the twenty-six lakes sampled (Vol. 1, Table 1) are displayed in Volume 3: Data and Results for each of the lakes, and are commented on and interpreted for the each lake individually in Chapters 2 to 27 of this volume. Volume 1: General Findings discusses the findings of the LMP.

CHAPTER 2

2.0 LAKE OMAPERE

Lake Omapere is a shallow, Northland lake which has been used as a water source for the town of Kaikohe. It is set in rolling farming country and is fairly large; it is slightly oval in shape with the larger and smaller diameters being approximately 4.7 and 3.4 kms in lengh. The bathymetry of the lake is that of a bowl which has a maximum depth of a little more than 1.9m. The lake has a history of oscillating between macrophyte and phytoplankton dominance. It was sampled 94 times from February ’92 to June ’96. Since two depths were sampled on each occasion, there are about 182 values for most variables. There are 94 values for Chla since only surface samples were taken and 78 values for suspended solids which were sampled from the surface from January ’93. Fig. 2.0 shows the position of the sampling stations.

2.1 Physical Variables

2.1.1 Lake Depth

Annualised lake depth varied from a low of 1.55m in February to a high of 2.0m in August, with a significant ($p<0.01$) increase of 0.034 m yr^{-1}(Fig. 2.1B).

2.1.2 Lake Temperature

Annualised temperature varied from a high of 22^{o}C in January to a low of 11.55^{o} in July (Fig. 2.1C). There was a significant ($p<0.01$) increase in temperature of 0.42^{o}C yr^{-1} (Fig. 2.1D).

2.1.3 Suspended Solids

As Lake Omapere is about 2m deep, it is unstratified all year and is easily mixed vertically. Since wind induced mixing can be a dominant factor in small lakes, suspended solids were sampled from 1993 onwards as an indirect measure of wind mixing because suspended solids provide a measure of the quantity of material stirred from the lake bottom. Fig. 2.1E shows that there is no pattern of TSS concentration during the year. Fig. 2.1F shows high TSS values during 1993 which substantially decreased in 1994, 1995 and early 1996 with higher concentrations again observed after February 1996. There was a significant ($p<0.01$) decrease in TSS values over the time of observation. The decrease in the TSS concentration was followed by an increase in the bottom coverage of the lake by *Egeria densa* (Champion 1995).

2.2 Trophic State Variables

Figs. 2.1G,H show that, by virtue of the low correlation coefficient values (R), there was very little seasonal effect in Chla and SD values. Thus there is little point in trying to correct the Chla and SD values for seasonality by means of the annualised curves. Figs. 2.2B,F,H show that the Chla, TP and TN content of the lake declined remarkably from 1992 to 1996. Was this decline due to a real decrease in the availability of nutrients from the catchment or to a diminished recycling of nutrients from the sediments? In other words, if the plants covering the sediments were to collapse and disappear as was the case in 1992, would the lake revert to its 1992 state? Figs. 2.2A,C,E,G show the results of correlations of Chla, SD, TP and TN with TSS and show that changes in these four variables were strongly related to TSS concentrations. The TSS content of the lake water is a direct measure of the degree of resuspension and the residuals shown in Figs. 2.2B,D,F,H which were calculated using the relationships shown in Figs. 2.2A,C,E,G indicate that the observed values of Chla, SD, TP and TN could result from resuspension of bottom sediments in Lake Omapere.

2.2.1 Chlorophyll *a*

Fig. 2.2A shows that there was a strong relationship between Chla and TSS and since the only real source of the large quantities of TSS which appeared and disappeared from the lake was the sediments, the conclusion is drawn that Chla concentrations are strongly affected by resuspension. Fig. 2.2B shows Chla concentrations plotted with time. The observed Chla content of Lake Omapere has declined logarithmically but the Chla, corrected for TSS, shows little change with time, indicating that the Chla decline is related largely to the increased coverage of the sediments with macrophytes which diminish the TSS content of the water and hence the nutrient content of the water. The CTS value for Chla in the lake water is -3 because the lake has switched from a phytoplankton to a macrophyte dominated state and the water quality is much improved. Overall there appears to be no change in the external load of nutrients to the lake. The linear decrease in Chla is -7.3 mg m^{-3} yr^{-1} and the average concentration is 13.4 mg m^{-3} giving a PAC of -55% yr^{-1}.

2.2.2 Secchi Depth

Fig. 2.2C shows a strong inverse relationship of SD with TSS. This is confirmed by Fig. 2.4D where the inverse of SD, namely Opacity, is plotted against ISS. Fig. 2.2D shows that there has been a significant ($p<0.01$) improvement in the observed SD but there has been no real change in SD when it is corrected for resuspension effects. The CTS value for SD change in the lake water is -3 because of a decrease in the effects of resuspension. The change in SD is 0.18m yr^{-1} and the average value is 0.77m so that the PACx-1 is -23% yr^{-1}.

2.2.3 Total Phosphorus

Fig. 2.2E shows that the TP content of the water is strongly related to the TSS content. Fig. 2.2F shows a significant ($p<0.01$) drop in the TP in the water with time but the TP corrected for resuspension effects does not show any change. The CTS value for changes in the TP content of the lake water is -3 because it is derived from observed change in water quality of the lake. The change in TP is -19.7 mg P m^{-3} yr^{-1} on an average value of 53 mg P m^{-3} giving a PAC of -37% yr^{-1}.

2.2.4 Total Nitrogen

Fig. 2.2G shows that the TN content of the water is strongly related to the TSS content. Fig. 2.2H shows that the TN content of the lake water has decreased significantly ($p<0.01$). The TN concentration corrected for the TSS content of the water showed no change with time. The CTS value for change in the lake water is -3. The decrease in TN is -116 mg N m^{-3} yr^{-1} on an average concentration of 573 mg N m^{-3} giving a PAC of -20% yr^{-1}.

Should corrections be made for resuspension effects?

The ISS material can only have originated from the lake floor and this is the most direct measure of resuspension of sediment, even more so than TSS which contains an organic component. Figs. 2.5A,C show that ISS and TSS were equivalent in predicting the amount of Chla in the water. TSS has been used as the variable to remove the effects of resuspension on the four trophic state variables, Chla, SD, TP, TN. Figs. 2.5D,F,G,H show that turbidity is also strongly related to the four trophic state variables and raises the possibility of using turbidity as an indirect indicator of resuspension as it is cheaper to measure turbidity than to measure TSS and ISS. This situation was investigated as shown below.

Many shallow lakes may not go through the massive changes that Lake Omapere has gone through and may have a stable macrophyte covering. To check this situation, the Lake Omapere data was examined from October '93 to March '96 when TSS values were relatively low. There were 112 turbidity and 56 ISS measurements during this period. The results are shown in Fig. 2.4A to H. In all cases the ISS was a better predictor of Chla, SD, TP and TN values than turbidity, but in all cases the correlation coefficients were much lower than when the full data set, including high values of TSS, was used. The result from this small investigation is that TSS or turbidity can be used to correct for resuspension effects when massive resuspension occurs, but when little resuspension occurs it is not really possible to correct for it. It would appear that it is not important to correct for resuspension effects. Macrophyte surveys of the type described by Champion (1995) are most useful if large changes in the trophic state variables are observed, as they directly document the probable cause of the large changes.

2.3 Other Variables

Fig. 2.3D shows that there was a small but significant ($p<0.01$) increase in DRP concentrations, but the other plots in Fig. 2.3 show that turbidity, pH, conductivity NO_3, NH_4, ISS and OSS all decreased significantly ($p<0.01$) over the period of observation.

No oxygen depletion calculations can be usefully done on observed DO concentrations from an unstratified lake.

2.4 Phytoplankton Phenomena

Table 2.2 gives details on the number and biovolume of the phytoplankton species present. The biovolume of the most important species over the three year period of data collection is shown in Fig. 2.6.

The large drop in Chla (Table 2.1) has occurred mainly due to the decrease in the biomass of *Aulacoseira ganulata*.

2.5 Conclusions

Lake Omapere has undergone massive change from being phytoplankton dominated to being macrophyte dominated. This has diminished resuspension of sedimentary materials and nutrient regeneration, which has led to decreased phytoplankton density and improved water clarity. However, the data on the four trophic variables Chla, SD, TP and TN when corrected for resuspension effects using TSS values showed little change with time, so almost all the change in the lake is related to the growth of macrophytes, diminishing the release of dissolved nutrients from the bottom of the lake and the resuspension of sedimentary materials. There has been little or no change in the catchment use which could lead to change in the external loading of nutrients to the lake.

Table 2.0

Lake Omapere	Chla	SD	TP	TN	Avs. of PAC, CTS values and of TLx=TLI values	Std. Err.	p-value
PAC (%/yr)	-55	-23	-37	-20	**-34**	8	0.02
CTS (units/yr)	-3	-3	-3	-3	**-3**	0	<0.01
TLx - 1992	6.09	6.45	6.1	5.23	**5.97**	0.26	
TLx - 1993	5.18	5.56	5.51	4.86	**5.28**	0.16	
TLx - 1994	3.59	4.97	4.31	4.08	**4.24**	0.29	
TLx - 1995	4.56	5.09	4.65	4.53	**4.71**	0.13	
Avs. Of TLc, TLs, TLp, TLn, TLI, p-values	**4.86**	**5.52**	**5.14**	**4.68**	**5.05**	0.19	**0.01**
Time Trend in TLI = -0.48 ± 0.22 units/yr. Trend is confirmed							

The table above is a summary of the time trend monitoring results obtained for Lake Omapere. The average PAC value of -34 ± 8% yr^{-1} indicates a very large degree of change to a lower trophic level and the CTS value of 3 ± 0 units indicates a high probability that this change has occurred. The average TLs value of 5.52 units is much higher than the other average TLx values, indicating that this lake is very turbid for its trophic level. This is to be expected for a shallow, wind swept lake. The TLI value change from 6.0 ± 0.3 (rounded off) in 1992 to 4.7 ± 0.1 in 1995 at the rate of 0.5 ± 0.2 TLI level units per year is a very rapid rate of rate of change of level so that Lake Omapere has basically changed from a hypertrophic to eutrophic lake in the 4 year monitoring period. The low average PAC and CTS p-value of 0.01 confirms the TLI time trend.

Data revealed that turbidity is as good an indicator of change as TSS and ISS when massive change has occurred. However, when the system is stable and relatively little resuspension occurs, ISS is no longer a good predictor of Chla, SD, TP and TN values and turbidity, under these circumstances, is an even weaker predictor.

Invaluable information explaining some of the changes observed in Lake Omapere were obtained from the macrophyte surveys carried out by Champion (1995). Macrophyte surveys should form part of the monitoring methodology for shallow lakes especially when changes in the trophic state variables are noticed.

CHAPTER 3

3.0 LAKE WHANGAPE

Lake Whangape is one of the larger shallow Waikato lakes and has very high national wild life values. It is shaped somewhat like an X with the longer axis being 7.6 km and the shorter axis about 4.5 km long. The majority of the lake varies between a depth of 2.0 and 2.5m. Lake Whangape was sampled 86 times for Chla, 44 times for LD and 170 times for most other variables from April 1992 to June 1996. Fig. 3.0 shows an outline of Lake Whangape with the location of the sampling stations.

3.1 Physical Variables

3.1.1 Lake Depth

The annualised data show a fairly strong pattern (R=0.66) of lake depth varying from a minimum of 1.3m to a maximum of 2.7m deep (Fig. 3.1A). The deseasonalised data showed ($p<0.01$) an increase in depth of 0.21m yr^{-1} (Fig. 1B).

3.1.2 Temperature

The annualised temperature varied from a high of 23^o to a low of 11^oC (Fig. 3.1C). The time trend did not show a significant temperature change from 1992 to 1996 (Fig. 3.1D).

3.1.3 Dissolved Oxygen

DO % saturation was above 100% in the late summer and early winter (Fig. 3.1G) but below 100% saturation in spring. There does not appear to be any long term trend (Fig. 1H).

3.1.4 Suspended Solids

ISS is important as it gives a measure of sediment disturbance, with slightly less disturbance evident in the autumn-winter than spring-summer (Fig. 3.1E). However, the time trend analysis shows ($p<0.01$) the considerable decrease in ISS with time of 21 gm^{-3} yr^{-1} which is 58% of the average value 36 gm^{-3} (Fig. 1F, Table 3.1). A similar pattern is observed with TSS (Fig. 3.4G) which decreased by 27 gm^{-3} yr^{-1} or

57% of the average value of 48.2 gm^{-3}. OSS decreased by 6.5 gm^{-3} yr^{-1} which is 53% of the average value of 12.2 gm^{-3} (Fig. 3.4H).

3.2 Trophic State Variables

When analysing the data from the four trophic state variables, Chla, SD, TP and TN for shallow lakes, it is important to determine whether their concentrations depend on the ISS concentration or other factors. A plot of Chla against ISS (Fig. 3.2A) shows that two different relationships between these variables seem to exist. From September 1993 to January 1994 the Chla concentration was 0.08 times that of ISS (Fig. 3.2D) but during the rest of the period it was 0.73 times the ISS concentration (Fig. 3.2C) or almost ten times stronger.

A similar pattern is seen with the TP/ISS relationship (Fig. 3.2E) where the TP collected between September 1993 and January 1994 (Fig. 3.2H) had a different relationship to that collected at other times (Fig. 3.2G). SD and TN vs ISS demonstrated similar patterns but are not shown here. As a result of these differing relationships, ISS was not considered to be the controlling variable and corrections were not made to the trophic state variables on the basis of ISS concentration.

3.2.1 Chlorophyll *a*

Chla shows a weak pattern of being slightly higher in the summer and lower in the winter (Fig. 3.3A). The time trend shows Chla to decrease ($p<0.01$) by 5.2 mg $m^{-3}yr^{-1}$ to yield a PAC of

-21% yr^{-1} of the average value of 24.0 mg m^{-3} (Fig. 3.3B) and a CTS value of -3 for Chla.

3.2.2 Secchi Depth

SD shows higher values in autumn (Fig. 3.3C) and an increase with time of 0.16m yr^{-1} (Fig. 3.3D). This represents a PAC x -1 of -27% yr^{-1} of the average annual value of 0.54m and gives a CTS value of -3. SD, in the form of opacity, showed two different relationships with ISS (Figs. 3.5C,D), there being one relationship when high values of ISS were measured (Fig. 3.5C) and another when lower values of ISS were observed (Fig. 3.5D). The reasons for this are not known.

3.2.3 Total Phosphorus

TP values are slightly lower in the winter (Fig. 3.3E) and have trended downward by 18 mg m^{-3} yr^{-1} yielding a PAC of -26% yr^{-1} of the average value of 68.7 mg m^{-3}. This yields a CTS value of -3.

3.2.4 Total Nitrogen

There is no annual pattern in the TN concentrations (Fig. 3.3G) which have trended downward ($p<0.01$) by 84 mg m^{-3} yr^{-1} yielding a PAC of -10% per year of the average value of 820 mg m^{-3}. This gives a CTS value for TN of -3. TON (Fig. 3.5A) shows more annual variation than TN and shows a greater decline with time of 133 mg N m^{-3} yr^{-1}.

3.3 Other Variables

Turbidity showed a decrease ($p<0.01$) which is consistent with the increase in SD (Figs. 3.4A, 3.3D). EC also showed a decrease (Fig. 3.4C). DRP showed an increase (Fig. 3.4D) which may be the result of temporary anoxia in the surficial sediments in recent times because of the lack of vertical mixing following increased macrophyte cover (Champion et al. 1996). There is an incidence of high ammonia release from the deeper samples on 12 February 1996 (Fig. 3.4F). This is probably the result of low oxygen concentrations near the bottom because NH_4 is released when low oxygen conditions occur. High NO_3 concentrations (Fig. 3.4E) indicate release of NH_4 which has subsequently been oxidised.

3.4 Phytoplankton Phenomena

The phytoplankton species composition and biomass observed in Lake Whangape is shown in Table 3.2. Changes in the dominant phytoplankton are shown in Fig. 3.6. There has been a decline in the contribution of the euglenoids with a corresponding increase in the contribution of greens and some cyanobacteria *(Anabena)*.

3.5 Conclusions

Lake Whangape has changed in recent years. Champion, Wells and de Winton (1996) have described changes in the macrophyte cover of this lake. Evidently, the macrophytes in this lake collapsed in 1987 leaving bare sediment over 90% of the lake. *Ceratophyllum demursum* began to spread from remnants which survived the collapse and by 1991 covered 30% of the lake. By May 1996, virtually the whole lake had 75% cover of *C. demursum*. This increase in surface reaching macrophyte coverage explains the increase in SD and decreases observed in suspended solids, Chla, TP and TN as vertical mixing is markedly diminished by macrophytes. This change in the water quality of the lake from a phytoplankton dominated system to a macrophyte dominated one is reflected in the values shown in the table below.

Table 3.0

Lake Whangape	Chla	SD	TP	TN	Avs. of PAC, CTS values and of TLx=TLI values	Std. Err.	p-values
PAC (%/yr)	-24	-27	-26	-10	**-21**	3.7	0.01
CTS (units/yr)	-3	-3	-3	-3	**-3**	0	<0.01
TLx - 1992	6.2	6.01	5.93	5.39	**5.88**	0.17	
TLx - 1993	5.94	6.13	6.12	5.4	**5.9**	0.17	
TLx - 1994	5.45	5.76	5.1	4.99	**5.32**	0.17	
TLx - 1995	4.86	5.37	4.99	5.08	**5.07**	0.11	
Avs. Of TLc, TLs, TLp, TLn, TLI, p-values	**5.61**	**5.81**	**5.54**	**5.22**	**5.54**	0.12	**0.01**
Time Trend in TLI = -0.30 ± 0.08 units/yr. This is confirmed.							

The average PAC value shows a large decline in the trophic state variables of -21 ± 3.7% yr^{-1} and this is confirmed as being most probable by the CTS value of 3.0 ± 0.0 units. The TLx values for all the variables declined each year leading to a low values for PAC and CTS average p-value, which confirms the value of the TLI time trend of -0.3 ± 0.1 yr^{-1}. The lake has almost changed a whole trophic level from 5.9 ± 0.02 to 5.1 ± 0.1 level units. The average TLx values are all similar, indicating that these variables are in reasonable balance with each other in terms of the lakes monitored in the LMP.

CHAPTER 4

4.0 LAKE ROTOROA (HAMILTON LAKE)

Lake Rotoroa lies within the city of Hamilton and is about 1.8km long by 0.4 km wide. For many years it supported a widespread growth of macrophytes which declined and finally disappeared in 1990. The lake then suffered intense algal blooms for several years. Lake Rotoroa was sampled 92 times which yielded 92 Chla and SD values and 142 nutrient and 121 suspended solids values for the epilimnion or isothermal conditions. There were relatively brief stratified periods which yielded 18 hypolimnetic nutrient and suspended solids values. An outline of Lake Rotoroa with the sampling stations marked is shown in Fig. 4.0.

4.1 Physical Variables

4.1.1 Lake Depth

Figs. 4.1A,B shows the lake depth dropping in the late summer, due to evaporation lowering the lake level below the drainage sill. Fig. 4.1B shows no change in the lake level with time.

4.1.2 Lake Temperature

Fig. 4.1C shows a normal range of annualised lake temperatures from 10 to 23^{o}C for surface waters. Fig. 4.1D shows that the temperature increased by 0.3^{o}C per year. The hypolimnion temperatures are unusual in that they are similar to the prevailing epilimnion temperatures (Fig. 4.1E,C). This indicates a major degree of intermixing between these two water masses. The relatively brief periods of stratification (except for the 1993/4 summer) are shown in Fig. 4.1F. The weak nature of the thermal stratification is shown in Figs. 4.4 A,B, with little change in temperature with depth.

4.1.3 Dissolved Oxygen

Fig.1G shows the variability in DO concentrations in the hypolimnion with concentrations increasing rapidly when downmixing of surface waters occurs and depleting rapidly during calm periods with little downward mixing. The hypolimnetic nutrient values (Table 4.1) do not show complete removal of NO_3 or massive regeneration of NH_4 or DRP. This is a strong indication that anoxic conditions did not occur in the surficial sediments of Lake Rotoroa. It is not possible to calculate meaningful DO depletion rates under the mixing regime which prevails in Lake Rotoroa.

4.2 Trophic State Variables

4.2.1 Chlorophyll *a*

Fig. 4.2A shows little annual variation in Chla concentrations but Fig. 4.2B shows a significant (2% s.l.) decrease of Chla with time of 1.7 mg m^{-3} yr^{-1} or a PAC of -10.6% per year of the average level of 16.3 mg Chla m^{-3} and yields a CTS value of -2.

4.2.2 Secchi Depth

Fig. 4.2C shows a pattern of low clarity in late summer followed by an increase in clarity in the winter. There was an increase ($p<0.01$) in SD of 0.05m yr^{-1} or a PAC x -1 of -4.8% per year on the average SD of 1.05m (Fig. 4.2D). This yields a CTS value of -3.

4.2.3 Total Phosphorus

Fig. 4.2E shows little variation in TP values through the year but Fig. 4.2F shows a decrease ($p<0.01$) of 2.9 mg P m^{-3} yr^{-1} or a PAC of -10.8% per year. This yields a CTS value of -3. Hypolimnetic TP (Fig. 4.3A) shows no pattern.

4.2.4 Total Nitrogen

Fig. 4.2G shows a pattern of TN increase above background level during spring. This is probably a result of the increase in NO_3 (Fig. 4.3C) at this time of year. TN decreased markedly ($p<0.01$) during the observation period at the rate of 155 mg N m^{-3} yr^{-1} to yeild a PAC of -16.8% per year of the average value of 923 mg N m^{-3}. This yields a CTS value of -3. Hypolimnetic TN also shows a pattern of decreasing concentrations with time (Fig. 4.3B).

Changes in TON were less dramatic than in TN but show that there was a definite decrease in suspended organic matter in the lake (Figs. 4.5A,B). The TON change with time is similar to that of OSS (Fig. 4.4G).

4.3 Other Variables

4.3.1 Nitrate

Fig. 4.3C shows a pattern of epilimnetic NO_3 concentrations increasing during the winter to a maximum in the spring and then decreasing rapidly thereafter. Fig. 4.3D shows low, but detectable amounts of NO_3 in the hypolimnion. There was a decrease in concentrations in epilimnetic NO_3 with time of 6.8 mg N yr which is about 18.5% per year of the average level of 36.7 mg N m^{-3}.

4.3.2 Ammonia

Epilimnetic ammonia showed a marked decrease ($p<0.01$) of 102 mg N m^{-3} yr^{-1} from an average concentration in 1992 of 465 to 95 mg N m^{-3} in 1995/96 (Fig. 4.3E, Table 4.1). The drop in NH_4 concentrations is a major factor in the TN decrease with time. The hypolimnetic NH_4 values were high on occasion and at the level found in the surface waters, indicating little anoxic release (Fig. 4.3F).

4.3.3 DRP

Epilimnetic DRP showed a small but significant ($p<0.01$) increase of 0.2 mg P m^{-3} yr^{-1} (Fig. 4.3G) in contrast to all the other nutrient levels which were decreasing with time. In 1992, very low values of DRP were observed (Table 4.1) when high concentrations of NO_3 and NH_4 were present, and thus at that time phosphorus availability was limiting to phytoplankton growth. The low values of NH_4 and NO_3 and the relatively high values of DRP observed in December ’95 to March ’96 indicated that nitrogen rather than phosphorus was limiting to growth at that time (Figs. 4.3C,E,G). Low values of hypolimnetic DRP (Fig. 4.3H) indicated that anoxic conditions did not occur.

4.3.4 Other Variables

Turbidity declined (Fig. 4.4C) as might be expected with an increase in SD. Conductivity (Fig. 4.4E) and pH (Fig. 4.4D) did not show any particular trend.

4.3.5 Suspended Solids

Fig. 4.4F shows that TSS decreased with time and that this decrease was largely a result of a decrease in OSS (Fig. 4.4G). It is of interest that the trend line for ISS, although not significant, showed no change with time. In other words, the amount of resuspension from the bottom has probably remained constant over time. This fits in with the observation of Burns et al. (1997b) that there has not been a noticeable change in the amount of sediment coverage by macrophytes.

4.4 Phytoplankton Phenomena

Recent periods of dominance by diatoms *(Asterionella formosa)*, blue-green algae *(Microcystis aeruginosa)* and the increasing dominance of the chrysophyte, *Dinobryon divergens* (Fig. 4.6) probably reflect changes in the nature of nutrient availability. These changes, however, do not indicate a significant change in trophic status from the mesotrophic-eutrophic state reported by Chapman and Green (1987).

4.5 Conclusions

As mentioned in section 4.1.3, HVOD rates could not be calculated. It would seem that the lake waters became very eutrophic when the macrophytes collapsed in 1989 and returned much of their nutrients to the water. This caused the phytoplankton bloom conditions noted by Clayton and de Winton (1994) in the period prior to 1992. In 1992 growth appeared to be phosphorus limited (Fig. 4.3G) with an adequate supply of nitrogen nutrients (Figs. 4.3C,E) but the supply of nitrogen nutrients has decreased to the point that growth can be limited by either nutrient. Phytoplankton growth is now diminishing with time (Fig. 4.2B). The four trophic state variables have given clear indication that Lake Rotoroa has become less eutrophic from March 1992 to June 1996 as shown in the table on the next page.

Table 4.0

Lake Rotoroa	Chla	SD	TP	TN	Avs. of PAC, CTS values and of TLx=TLI values	Std. Err.	p-values
PAC (%/yr)	-10.6	-4.8	-10.8	-17	**-11**	2.5	0.02
CTS (units/yr)	-2	-3	-3	-3	**-2.75**	0.25	0.02
TLx - 1992	5.70	5.20	4.64	5.68	**5.30**	0.25	
TLx - 1993	5.15	4.94	4.31	5.55	**4.99**	0.26	
TLx - 1994	5.28	4.98	4.46	5.07	**4.95**	0.17	
TLx - 1995	4.99	4.98	4.07	4.99	**4.76**	0.23	
Avs. Of TLc, TLs, TLp, TLn, TLI, p-values	**5.28**	**5.03**	**4.37**	**5.32**	**5.00**	0.11	**0.02**
Time Trend in TLI = -0.17 ± 0.04 units/yr. This is confirmed.							

The results summarised in the table above show that the improvement in Lake Rotoroa has been substantial with a PAC value of -11 ± 2.5% yr^{-1} and considered to be most probable because of the CTS value of 2.75 ± 0.25 units. All the TLx values show a decline with time as does the TLI, which has a time trend value of -0.17 ± 0.04 units. This time trend value is confirmed by the low average of 0.02 of the PAC and the CTS average p-values. The lake has changed its trophic level from supertrophic at a TLI of 5.3 ± 0.3 units in 1992, to eutrophic at 4.8 ± 0.2 units in 1995. The phosphorus limitation to growth deduced from the DRP data was confirmed by the TLp being much lower than the other TLx values.

CHAPTER 5

5.0 LAKE MARATOTO

Lake Maratoto is representative of the Waikato peat bog lakes; its waters are stained brown. It lies in rolling farmland, is about 700m long and has a maximum depth of 7.1 m. There were a number of peat fire in its catchment in 1992 which may have had some effect on the lake. Chla and SD were sampled 85 times; TN was sampled 126 times and most other variables were sampled 151 times in the epilimnetic or isothermal waters of Lake Maratoto. An outline of the lake with the sampling stations marked is shown in Fig. 5.0.

5.1 Physical Variables

5.1.1 Lake Depth

Lake depth varied between 6.3 and 7.2m in an unpredictable manner (Fig. 5.1A) and did not vary significantly with time (Fig. 5.1B).

5.1.2 Lake Temperature

Annualised surface water temperatures varied between 23.5 and 10.0^{o}C (Fig. 5.1C) and increased ($p<0.02$) at 0.15^{o}C yr^{-1}. The lake stratifies intermittently with relatively weak stratification and very high hypolimnion temperatures (Figs. 5.1G,H).

5.1.3 Dissolved Oxygen

Epilimnetic DO% saturation is high in early summer and low in late summer (Fig. 5.1E) due possibly to upward mixing of deoxygenated bottom waters at that time of year. There was a significant ($p<0.01$) increase in DO% saturation due possibly to the increased phytoplankton growth (Fig. 5.2B).

Due to the rapid rate of HVOD (5g DO m^{-3} on 14 December 1993 to 0.0g in m^{-3} on 11 January 1994) and the existence of weak, intermittent stratification, reasonable HVOD rates could not be calculated for comparative purposes.

5.2 Trophic State Variables

5.2.1 Chlorophylla *a*

Annualised Chla showed a weak pattern of higher concentrations in the late summer and lower ones in the winter (Fig. 5.2A). Fig. 5.2B shows the remarkably strong ($p<0.01$) increase in Chla concentrations with time of 14.8 mg m^{-3} yr^{-1} or a PAC of 45% per year of the average concentration of 32.8 mg m^{-3}. This yields a CTS value of +3 for Chla.

5.2.2 Secchi Depth

SD in Lake Maratoto is comparatively low because of the highly coloured nature of the water which is stained by peat drainage. Fig. 5.2D shows a significant ($p<0.01$) decrease in the SD of the lake of -0.05m yr^{-1} as can be expected with the large annual increase in Chla. The PAC x -1 is 7.6% yr^{-1} and the CTS value for SD is +3.

5.2.3 Total Phosphorus

TP concentrations are higher in the autumn and lower in the spring (Fig. 5.2E). No trend in TP with time was observed and the CTS value for TP is 0.

5.2.4 Total Nitrogen

TN does not show a strong annualised pattern of concentration change (Fig. 5.2G) but does show a significant ($p<0.01$) decrease with time of -163 mg N m^{-3} yr^{-1}, yielding a PAC of -11% yr^{-1} and a CTS score of -3. TON also shows a decrease ($p<0.01$) with time (Fig. 5.4B) of -60.8 mg N m^{-3} yr^{-1} which indicates that there was a simultaneous decrease in both dissolved nitrogen nutrients and organic matter. This is most unexpected if one considers the strong increase in Chla occurring at the same time.

5.3 Other Variables

5.3.1 Turbidity

The trend of turbidity with time (Fig. 5.3A) is very similar to that of Chla with time (Fig. 5.2B). This is confirmed by the strong correlation of turbidity with Chla (Fig. 5.3G). The correlation of opacity (1/SD) with Chla is much weaker (Fig. 5.3H) and it can be inferred from this that turbidity is more sensitive to particulate matter in the water than is SD in Lake Maratoto.

5.3.2 pH and Conductivity

pH shows a significant increase ($p<0.01$) with time and EC a significant decrease with time (Figs. 5.3B,C), but the reason for these trends is not readily apparent. The average pH of 4.87 is very low for a New Zealand lake and reflects the dystrophic nature of Lake Maratoto.

5.3.3 Dissolved Nutrients

All three dissolved nutrients, DRP, NO_3 and NH_4 showed significant decreases with time. This is possibly as a result of the increased phytoplankton growth with time (Figs. 5.3D,E,F).

5.4 Phytoplankton Phenomena

The data for the phytoplankton samples which were analysed is shown in Table 5.2 and the changes in the dominant species is shown in Fig. 5.5. The occurrence of high levels of Dyakosoma pelophilium in the first year is considered to be due to a sampling anomoly. Excluding this anomaly, there appears to be an increase in eugleniod numbers including the species assicated with increased eutrophication (Trachelomonas sp.)

5.5 Conclusions

The results of the 1992-96 monitoring programme are very difficult to assess because while there is strong evidence of increased Chla concentration and phytoplankton growth there is no corresponding increase in total nutrient concentration. In fact, TON and TN values decreased significantly with time.

Table 5.0

Lake Maratoto	Chla	SD	TP	TN	Avs. of PAC, CTS values and of TLx=TLI values	Std. Err.	p-values
PAC (%/yr)	45	7.6	(+0.3)	-11	**10**	12.1	0.63
CTS (units/yr)	3	3	0	-3	**0.75**	1.44	0.45
TLx - 1992	5.12	5.34	4.44	5.96	**5.22**	0.31	
TLx - 1993	4.70	5.52	4.59	6.45	**5.31**	0.43	
TLx - 1994	6.39	5.42	4.60	5.70	**5.53**	0.37	
TLx - 1995	6.76	5.66	4.47	5.67	**5.64**	0.47	
Avs. Of TLc, TLs, TLp, TLn, TLI, p-values	**5.74**	**5.49**	**4.53**	**5.95**	**5.43**	0.18	**0.54**
Time Trend in TLI = 0.15 ± 0.02 units/yr. This trend is not confirmed.							

The above table shows the contradictory nature of the results obtained in Lake Maratoto as illustrated by the PAC values, with Chla showing a large increase of 45% yr^{-1} and TN showing a decrease of -11% yr^{-1}. The average PAC value is 10% yr^{-1} but is smaller than its standard error of 12.1% yr^{-1}. This means that the PAC indicates no change in the lake and this outcome is confirmed by the average CTS value of 0.75 units which is also smaller than its standard error of 1.44 units. The increases in the TLc and TLs are so large that the annual TLI values increase uniformly with time and give a time trend for the TLI of 0.15 ± 0.02 units yr^{-1}. This value indicates a steady increase in trophic level and in this case the TLI contradicts the signals given by the PAC and CTS indicators. The average of the PAC and CTS average p-values is high, indicating no change and the TLI is thus judged to be giving an erroneous indication of change. The relatively low value of TLp indicates that Lake Maratoto is phosphorus limited and thus the decrease in TN did not affect the phytoplankton growth. However, the strong trend of increasing Chla concentration indicates that Lake Maratoto should be monitored in the near future to determine the nature of the Chla concentration increases. The macrophytes of Lake Maratoto have not been monitored. It is possible that there has been some type of macrophyte collapse in the lake, leading to the phytoplankton increase, but this is not likely as this would have caused an increase in TP and TN and this was not observed.

CHAPTER 6

6.0 LAKE ROTORUA

Lake Rotorua was chosen to be monitored partly because of its high tourism value and partly to follow changes in the lake after the diversion of sewage input from it to surrounding forest in1991. It is an almost circular lake with a diameter of about 9.5 km. Lake Rotorua was sampled under two different regimes. From March 1989 to August 1994 the lake was sampled quarterly at 1m depth at a station close to RORS by Dr J Hall. From February 1992 to November 1992 and September 1994 to June 1996 the lake was sampled as part of the LMP. There were 91 samplings for Chla, 241 for TP and TN, 91 SD measurements, 211 measurements of DRP, turbidity, pH, EC with 260 values for NO_3 and NH_4. The position of the sampling stations are shown in Fig. 6.0.

6.1 Physical Variables

6.1.1 Lake Depth

LD was lowest in summer and increased by 20 cm during the winter (Fig. 6.1A). LD increased ($p<0.01$) with time by the small amount of 2.3 cm yr^{-1}.

6.1.2 Lake Temperature and Dissolved Oxygen

The annualised lake temperature shows an annual change from 21.5^{o}C in the summer to 9^{o}C in the winter (Fig. 6.1C) and showed an increase ($p<0.01$) of 0.3^{o}C yr^{-1} (Fig. 6.1D). Four T/DO profiles, from the three different sampling stations, which show the lowest DO concentration observed, are shown in Figs. 6.1E-H. The temperature differences surface to bottom were very slight even in the deep station, RORE (Fig. 6.1E). The lake is normally well mixed and the occasions of summer thermal stratification are brief. However, the near bottom water can go anoxic and release nutrients but these occasions of anoxia are often not observed; only the resulting high nutrient concentrations in water near the bottom are sometimes observed (Figs. 6.5D,E).

6.2 Trophic State Variables

6.2.1 Chlorophyll *a*

Chla values are usually highest in the late autumn (Fig. 6.2A). The time trend data (Figs. 6.2B,D,F) show an unusual pattern of steady Chla concentration decline from March 1989 to October 1991, after which the concentration remains constant for almost four years. The sewage load to Lake Rotorua ceased in October 1991. It is possible that the sewage input was decreasing prior to its cut-off date and the constant concentration of Chla since that date reflects an adjustment to the new load. It would seem that the long term time trend plot (Fig. 6.2B) is not appropriate to the data and that Figs. 6.2D,F having two straight line segments, are better approximations to the data. Visually, the Chla concentrations before and after October 1991 appear different but an appropriate statistical check would be to perform a t-test to see if the data before and after October 1991 are different. Before October 1991 the Chla mean was 17.9 ± 1.8 and after that date was 10.2 ± 0.4 with a p-value = 0.0002 for the two different sets of data. The Chla can thus be considered to have changed and Chla has CTS value of -3. Fig. 6.2B shows an average change in Chla of -1.15 mg m^{-3} yr^{-1} on an average concentration of 11.4 mg m^{-3}, to yield a PAC value of 10.1% yr^{-1}.

6.2.2 Secchi Depth

Unfortunately the record of SD data was brief and Fig. 6.2H shows little change in SD after 1991. There is no CTS or PACvalue for SD.

6.2.3 Total Phosphorus

TP is different from Chla in that the level of TP in Lake Rotorua does not appear to have changed from 1989 to 1996 (Fig. 6.3B) although Figs. 6.3D,F show a decline during 1989 to 1991. A t-test analysis of the two sets of data before and after October 1991 shows no significant difference between them with a p-value = 0.80. The CTS and PAC values for TP are 0. Fig. 6.3G shows that TP does not change significantly with depth.

6.2.4 Total Nitrogen

The changes in TN concentrations with time are similar to those of Chla with a decline ($p<0.01$) from March 1989 to October 1991 and a more or less unchanged concentration after that (Fig. 6.4D,F). The average concentration of TN before October 1991 was 361 ± 15.0 and 293 ± 5.3 after that date. The t-test result is that the two sets of data are different at the p = 0.0001 level. The CTS value for TN is -3.

Fig. 6.4B shows an annual average change of -4.16 mg N m^{-3} yr^{-1} on an average concentration of 299 mg N m^{-3} for a PAC value of -1.4% yr^{-1}. Fig. 6.4G shows that TN does not change significantly with depth.

6.2.5 Total Organic Nitrogen

The TON time trend (Fig. 6.7B) shows a much clearer pattern of decrease with time than does TN (Fig. 6.4B). The removal of the effect of NH_4 and NO_3 from the TN values reveals a decrease ($p<0.01$) in TON in agreement with the observed decrease in Chla.

6.3 Other Variables

6.3.1 Nitrate

Fig. 6.5A shows that NO_3 values do not change with depth and Fig. 6.5C shows also that the observed values did not change with time, although high values were observed in the autumn of 1995. These high values of NO_3 may have resulted from the oxidation of the ammonia released in the spring of 1995 (Fig. 6.5D).

6.3.2 Turbidity

Turbidity does not increase with depth (Fig. 6.5B) which is somewhat unexpected because resuspension from the bottom could be expected to give higher values for turbidity for near-bottom samples. Nevertheless, Fig. 6.5F shows a decline ($p<0.01$) in turbidity in the lake. SD measurements tend to agree with this observation because SD tends to have increased with time (Fig. 6.2H).

6.3.3 Ammonia

The NH_4 time trend (Fig. 6.5D) is interesting in that it is increasing with time ($p<0.01$) while the TN value is decreasing with time. The 1995 and 1996 episodes of high ammonia concentrations were in the late summer, indicating anoxic release of NH_4 but these releases did not raise the TN value to that of the pre-October ’91 levels.

6.3.4 Dissolved Reactive Phosphorus

DRP shows episodes of high concentration in 1995 and 1996 at the same time that high concentrations of NH_4 were observed (Figs. 6.5E,D). This corroborates the idea that there was anoxic release of nutrients in the summers of 1995 and 1996. These DRP releases appear to have prevented the TP level from dropping (Fig. 6.3D).

6.3.5 pH and Conductivity

Both pH and EC have decreased ($p<0.01$) with time (Figs. 6.5G,H). The reason for the pH decrease is not obvious, but the EC decrease may be due to the removal of the sewage input, since this waste would have had a higher salinity than the lake water.

6.4 Phytoplankton Phenomena

Only one aggregated sample of Lake Rotorua phytoplankton was analysed and the results are shown in Table 6.2.

6.5 Conclusions

It is not possible to calculate an average annual change in Chla and TN because they changed rapidly from 1989 to 1992 with very little change from 1992 to 1996. Thus the averages for these variables have been calculated for the two time periods. They have been compared and found to be different. The TN values may have continued to decrease from 1992 to 1996, but this decrease was prevented by anoxic release of NH_4 in 1995 and 1996. These releases did not seem to occur in the earlier years (Fig. 6.5D). There was no observed change in TP from 1989 to 1996. TON showed a decrease with time. SD data were insufficient to give a CTS or PAC values for it.

The table below shows the p-values for both the PAC and the CTA averages to be 0.18, although the SD data is insufficient to yield either PAC or CTS values for this variable.

Table 6.0

Lake Rotorua	Chla	SD	TP	TN	Avs. of PAC, CTS values and of TLx=TLI values	Std. Err.	p-values
PAC (%/yr)	-10.1	no data	(+0)	-1.4	**-4**	3.1	0.18
CTS (units/yr)	-3	no data	0	-3	**-2**	1	0.18
TLx - 1995	4.62	3.89	4.93	3.80	**4.31**	0.28	
TLx - 1996	4.87	4.03	4.66	3.86	**4.36**	0.24	
Avs. of TLc, TLs, TLp, TLn, TLI, p-values	**4.75**	**3.96**	**4.80**	**3.83**	**4.33**	0.48	**0.18**
Time Trend in TLI was not determined.							

The p-value average of 0.18 indicates probable change in Lake Rotorua and in this case the change is to an improved condition. Since TLI values are only available for two years, they give no signal about change, but the the TLn and TLp values do indicate that the lake is nitrogen limited. The fact that TON has shown a steady decline (Fig.6.7B) is a further indication of improvement in the lake.

CHAPTER 7

7.0 LAKE DUDDING

Lake Dudding is a sand dune lake in a recreational reserve and is well used. It has the shape of a number 7 with the long arm having a length of about 620m and the short arm of about 300m. The lake was sampled for less than three years from February 1992 to May 1994. This is not a long enough period to establish a time trend and thus any significant time trend which is observed is not really meaningful. There were 59 epilimnion samplings with 52 Chla samples and 31 hypolimnion samplings. Fig. 7.0 shows a diagram of the lake and the position of the sampling stations. The lake has a long axis of about 600m in length.

7.1 Physical Variables

7.1.1 Lake Depth

In the autumn, the lake depth decreased (Fig. 7.1A) but did not change consistently in the spring. In the autumn of 1994 lake depth was lower than the previous autumn, giving a trend of decreasing depth. Lake Dudding is relatively shallow at 10.5m and only maintains stratification because of its relatively small size.

7.1.2 Temperature

The temperature range of the surface water was from 8 to 21^{o}C (Fig.7.1C) and showed an increase with time (Fig. 7.1D). The hypolimnion temperature rose rapidly during the stratified period (Fig. 7.1E) and the hypolimnetic temperature was warmer in 1993/94 than 1992/93 (Fig. 7.1F).

7.1.3 Dissolved Oxygen

Fig. 7.1G shows the hypolimnion deoxygenating rapidly and remaining anoxic for most of the stratified period. This is shown in greater detail in Fig. 7.1H where all of the oxygen observed in October of 1992 and 1993 was depleted by the sampling a month later. This made it impossible to determine HVOD rates under a monthly sampling regime.

7.2 Trophic State Indicators

7.2.1 Chlorophyll *a*

Fig. 7.2A shows that Chla concentrations were variable in the autumn but similar in the winter and spring. No significant change with time was observed (Fig. 7.2B) over the short period of sampling.

7.2.2 Secchi Depth

SD showed considerable variation at any time of the year (Fig. 7.2C) and no significant trend with time (Fig. 7.2D).

7.2.3 Total Phosphorus

TP showed no particular pattern during the year (Fig. 7.2E) or from year to year (Fig. 7.2F). The average epilimnetic TP concentration of 42 mg P m^{-3} is high and the average hypolimnetic TP of 288 mg P m^{-3} is very high (Table 7.1). It is the result of the long period of anoxia when the lake is stratified. The development of the high TP hypolimnetic concentrations during the summer of 1992/93 is shown in Fig. 7.3A. Pdiff values were plotted (Figs. 7.5C,F) and also showed no change during the year or from year to year.

7.2.4 Total Nitrogen

TN concentrations were variable during the year (Fig. 7.2G). The significant decrease with time is due to the high winter-spring values for TN in 1992 (Fig. 7.2H). The average epilimnetic and hypolimnetic concentrations of 914 and 1821 mg N m^{-3} are very high (Table 7.1). The increase in hypolimnetic TN as the stratified season progresses is shown in Fig. 7.3B during the summer of 1992/93. The TON values (Fig. 7.5B) were less variable with time than those of TN (Fig. 7.2H) but there was no significant change in TON with time.

7.3 Other Variables

Very high NO_3 concentrations were observed in the epilimnion in the spring but they decreased rapidly (Fig. 7.3C). Exceptionally high NO_3 values were observed in the hypolimnion at the start of the stratified period (Fig. 7.3D) in 1992.

The epilmnetic NH_4 concentrations did not show a clear pattern (Fig. 7.3E) but these concentrations increased markedly in the hypolimnion in 1992/93.

Epilimnetic DRP concentrations varied considerably (Fig. 7.3G). Hypolimnetic DRP values increased to high values during the stratified period in 1992/93 but were relatively low during the stratified period in 1993/94. Traces of oxygen remained in the hypolimnion during 1993/94, probably due to downward mixing. This indicates that the supply of nutrients from the sediments of Lake Dudding could be highly variable.

Figs. 7.4A,B show Temperature/Depth profiles. The epilimnion usually extended to 5m depth and the hypolimnion usually commenced at 7m. The lake was isothermal on 20 September 1993 with DO concentrations of 10.8 g m^{-3} but a month later DO concentrations close to 0.0 g m^{-3} were observed near the bottom (Fig. 7.4A).

Epilimnetic turbidity showed massively high values in July 1992 (Fig. 7.4C) which corresponded with very low SD values (Fig. 7.2D). The lake was possibly churned up by a storm just prior to sampling.

The pH and EC values do not show any particular pattern.

7.4 Phytoplankton Phenomena

Only one aggregated sample of Lake Rotorua phytoplankton was analysed and the results are shown in Table 7.2.

7.5 Conclusions

There was no significant indication of change in Chla, SD and TP. TN showed a significant decrease. The value of the 2 year period of observation is largely that it described the stratified nature of the lake and established average values for the observed variables.

Table 7.0

Lake Dudding	Chla	SD	TP	TN	Average values of TLx=TLI value	Std. Err.
TLx - 1992	3.72	4.26	4.98	5.42	4.60	0.38
TLx - 1993	4.19	4.37	4.86	5.16	4.64	0.22
Avs. Of TLc, TLs, TLp, TLn, TLI, p-values	3.95	4.32	4.92	5.29	4.62	0.20
Time Trend in TLI was not determined.						

The TLI values in the table above indicate that the lake may have surplus nitrogen. The TLI of 4.6 ± 0.2 indicates the lake to be fairly eutrophic but not supertrophic.

CHAPTER 8

8.0 LAKE PEARSON

Lake Pearson lies in an extremely windy location that could be described as a mountain pass. The wind keeps the lake fully mixed all year although the deeper basin is 17m deep. It is about 2.4 km long with the north basin being about 650m wide. From March 1992 to June 1994 there were 48 sampling occasions with 96 samples taken for most variables. Although Lake Pearson is unstratified, samples were not analysed for TSS, ISS and OSS because it is relatively deep for an unstratified lake. An outline of the lake is shown in Fig. 8.0.

8.1 Physical Variables

8.1.1 Lake Depth

Fig. 8.1A shows Lake Pearson to have an average lake depth of 16.4m in the autumn which increases to about 17m in the spring. During the brief period of observation, the lake showed a significant (1%) increase in level (Fig. 8.1B).

8.1.2 Lake Temperature

Lake Pearson is relatively cold, with an annualised temperature reaching 16.5°C in the summer and dropping to 4°C in the winter (Fig. 8.1C). There was a significant ($p<0.01$) rise in temperature of 0.59°C per year.

8.1.3 Dissolved Oxygen

The epilimnetic % saturation of DO was lowest in midsummer and highest in the spring (Fig. 8.1E). There was a significant ($p<0.01$) drop in % saturation DO of 2.8% per year on an average value of 94.3% saturation.

8.1.4 Temperature, DO, Depth Profiles

Figs. 8.1G,H show almost identical profile shapes for temperature and DO in December and June, illustrating the lack of seasonal effect in this lake. However, Fig. 8.3G does show that in the summer some degree of temporary stratification can occur with lowered DO concentrations resulting. This stratification was short-lived, with the lake being well mixed a month later (Fig. 8.3H).

8.2 Trophic State Variables

8.2.1 Chlorophyll *a*

Chla showed a pattern of variable values in the first half of the year with much more predictable values in the later half of the year (Fig. 8.2A). The Chla values showed a significant ($p<0.01$) increase of 0.61 mg m^{-3} yr^{-1} or 55% of the average value of 1.1 mg m^{-3} Chla. This large increase is almost surely a result of the brief period of the measurement and does not represent a change of trophic state.

8.2.2 Secchi Depth

Fig. 8.2C shows that most SD observations were similar in magnitude with some very high and low values which can be expected in an unstratified lake with occasional calm or well stirred periods. There was no significant SD time trend.

8.2.3 Total Phosphorus

Fig. 8.2E shows that TP concentrations were highly variable at any time of the year with no significant trend in time. The Pdiff values (Fig. 8.4C,D) were very similar to the TP values.

8.2.4 Total Nitrogen

Fig. 8.2G shows TN to have a slight tendency to higher values in the autumn than in the spring. There was a significant ($p<0.01$) decrease in TN with time (Fig. 8.2H).

The pattern of change in TON (Figs. 8.4A,B) was similar to that of TN (Figs. 8.2G,H) but the decrease in TON with time was smaller because part of the decrease in TN was due to a decrease in NO_3 (Fig. 8.3E) with time.

8.3 Other Variables

Turbidity and pH showed no trend with time (Figs. 8.3A,B). There were significant decreases in EC ($p<0.02$) and NO_3 ($p<0.01$). However, DRP and NH_4 showed no change with time.

8.4 Phytoplankton Phenomena

Only two aggregated samples from Lake Pearson were analysed and the results are shown in Table 8.2.

8.5 Conclusions

Since Lake Pearson was only monitored for a little over two years, it is not possible to obtain reliable time trends from the data. The changes with time which were observed were probably more in the nature of a variation with time rather than a trend with time. Observations on the lake would have to continue for a longer period for genuine time trends to be established. The increase in temperature is probably genuine because it is similar to the temperature changes observed in other lakes.

Table 8.0

Lake Pearson	Chla	SD	TP	TN	Average values of TLx=TLI value	Std. Err.
TLx - 1992	1.88	3.17	2.52	2.77	2.59	0.27
TLx - 1993	2.16	3.24	2.83	2.62	2.71	0.22
Avs. of TLc, TLs, TLp, TLn, TLI	2.02	3.20	2.67	2.70	2.65	0.16
Time Trend in TLI was not determined.						

The table above shows Lake Pearson to be an oligotrophic lake with a TLI of 2.7 ± 0.2 but with a comparatively high TLs because it is unstratified and well mixed because of wind, causing a relatively high proportion of suspended material to be present in the water.

CHAPTER 9

9.0 LAKE FORSYTH

Lake Forsyth lies in the bed of a former river which used to flow into the sea and one end of the lake is only 250m from the sea. The lake is brackish and is about 6 km long with the main basin being about 1 km wide. There were 134 samples taken from Lake Forsyth for most variables but only 55 samples for the suspended solids variables from March 1992 to June 1995. An outline map showing the sampling stations is shown in Fig. 9.0.

9.1 Physical Variables

9.1.1 Lake Depth

The large basin of Lake Forsyth is only 1.6m deep but a much smaller basin has a spot which is 3.8m deep giving the lake a maximum charted depth of 3.8m. Fig. 9.1A shows a seasonal pattern of increasing depth to 4.35m in September from an autumn low of 3.9m in March. There has been a small significant ($p<0.01$) drop in the level of the lake (Fig. 9.1B) of 9.4 mm per year.

9.1.2 Lake Temperature

Fig. 9.1C shows a maximum annualised temperature of 19.5°C in February and minimum temperature of 7°C in July. Fig. 9.1D shows a significant ($p<0.01$) annual temperature increase of 0.64°C per year.

9.1.3 Suspended Solids

Figs. 9.1F, 9.3G,H show the time trend plots of ISS, TSS and OSS with average concentrations of 14.8, 23.9, 9.8 g m^{-3} (Table 9.1) respectively. ISS comprises 62% of the TSS on average. There is no significant time trend change in any of the three variables. Fig. 9.1E shows that there is almost no annualised pattern of variation in ISS.

9.2 Trophic State Variables

9.2.1 Chlorophyll *a*

Fig. 9.1G shows that there is virtually no annual pattern in the observed Chla concentrations, whereas Fig. 9.2A shows a significant (1%) correlation of Chla with ISS. Chla was thus corrected using observed ISS concentrations to obtain residual values for Chla. Since ISS is resuspended by wind, the correction for ISS was to see if there was any time trend when the weather induced effects of resuspension were removed from the data. Fig. 9.2B shows that there was no time trend in either the observed Chla data or that adjusted for ISS content.

9.2.2 Secchi Depth

The inverse of SD (opacity) was plotted against ISS and a significant ($p<0.01$) relationship observed, Fig. 9.2C. The opacity data was then corrected for the ISS content of the water but no time trend was seen in the residual opacity values or in the observed SD data (Fig. 9.2D).

9.2.3 Total Phosphorus

Fig. 9.2E shows that there was a significant ($p<0.01$) relationship of TP with ISS. However, there was no time trend in either the TP residual values after adjustment for the ISS content, or in the observed TP data (Fig. 9.2F).

The Pdiff values (Fig. 9.4A) show almost the same pattern as the TP data.

9.2.4 Total Nitrogen

Fig. 9.2G shows that there was no relationship between TN and ISS and therefore only the observed data for TN were plotted against time. A significant ($p<0.01$) downward trend of 129 mg N m^{-3} per year was found in the observed data which yields a PAC value of -18% per year on the average TN concentration of 684 mg N m^{-3}. The CTS value for TN was -3. The time trend for TON (Fig. 9.4B) is almost identical to that of TN, indicating very little change in NH_4 or NO_3.

9.3 Other Variables

9.3.1 Depth, Temperature, Dissolved Oxygen Profiles

Depth-T/DO profiles were not plotted because there was little change in temperature and DO with depth.

9.3.2 Turbidity

Fig. 9.3A shows that very high values for turbidity could be obtained on occasion, and the high values observed in the March of 1995 resulted in a weak ($p<0.05$) time trend being seen in the data. High values of TSS (Fig. 9.3G) observed at the same time, indicate that these high values of turbidity were the result of disturbance by strong winds.

9.3.3 pH

Fig. 9.3B shows that unusually high values of pH were observed in December 1994. This coincides with high values of 121% being observed for % Sat DO (Stn CHFS, 19 December 1994) indicating that the high values of pH were associated with high levels of phytoplankton growth.

9.3.4 Conductivity

An average EC of 6516 uS/cm for Lake Forsyth is unusually high for a lake (Table 9.1) and Fig. 9.3C shows values above 40,000 uS/cm. The high EC values were usually observed at the CHFS station which was closest to the sea and indicates occasional entry of seawater into the lake.

9.3.5 Dissolved Nutrients

Figs. 9.3D,E,F show that unusually high values of DRP, NO_3 and NH_4 were observed from time to time. The reasons for these high values are not obvious, but high values of EC were usually observed in the same samples.

9.4 Phytoplankton Phenomena

Only two aggregated samples from Lake Forsyth were analysed and the results are shown in Table 9.2.

9.5 Conclusions

There appear to be two strong disturbing influences on the lake, the first being wind, causing much resuspension and strongly affecting the values of variables which could be changed by resuspension. The other influence is related to high conductivity water, probably sea water, and the episodic intrusion of this water into the lake. The nature of these intrusions was not determined in this monitoring program.

Table 9.0

Lake Forsyth	**Chla**	**SD**	**TP**	**TN**	**Avs. of PAC, CTS values and of TLx=TLI values**	**Std. Err.**	**p-values**
PAC (%/yr)	(-4.4)	(+1.0)	(-1.6)	-18.8	**-5**	4.8	0.39
CTS (units/yr)	0	0	0	-3	**-0.75**	0.75	0.39
TLx - 1992	5.40	5.28	5.90	5.14	**5.43**	0.17	
TLx - 1993	5.72	5.49	5.91	5.30	**5.60**	0.13	
TLx - 1994	5.14	4.76	6.10	4.52	**5.13**	0.35	
Avs. Of TLc, TLs, TLp, TLn, TLI, p-values	**5.42**	**5.18**	**5.97**	**4.98**	**5.39**	0.14	**0.39**
Time Trend in TLI = -0.15 ± 0.18 units/yr which indicates no trend.							

The table above shows average PAC and CTS values of -5 ± 4.8 % yr^{-1} and -0.75 ± 0.75 respectively. These values indicate that the lake has not changed as does the time trend value for the TLI of -0.15 ± 0.18 units yr^{-1}. TLn seems to be relatively low when compared to the other TLx values but the lake does not appear to be nitrogen limited as the decrease in TN of -18.8% yr^{-1} does not seem to have decreased the Chla concentrations. The lake is supertrophic with a TLI of 5.4 ± 0.1.

CHAPTER 10

10.0 LAKE ALEXANDRINA

Lake Alexandrina lies in a catchment which has been used for grazing stock and that may have caused some eutrophication of the lake. It is about 7.1 km long with a width of approximately 1 km. There were 114 samplings of Lake Alexandrina's epilimnion or isothermal waters during the period of a little over three years. Fig. 10.0 is a diagram showing the majority of the lake and the position of the sampling stations.

10.1 Physical Variables

10.1.1 Lake Depth

Fig. 10.1A shows a weak annual pattern of lake depth variation. However, Fig. 10.1B shows a significant decline of 0.04 m yr^{-1} in lake depth.

10.1.2 Temperature

Fig. 10.1C shows an annualised summer high of 17^{o}C and winter low of 4^{o}C, both lower than the average temperature for most New Zealand lakes. A non-significant increase in temperature was observed, Fig. 10.1D. Figs. 10.1G,H and 10.3G show temperature/DO vs depth profiles for Lake Alexandrina.

This lake is best described as unpredictably stratified, some years forming a normal hypolimnion (Fig. 10.1G) briefly for a few months and other years the lower waters show a temperature graduation more in the nature of a thermocline (Fig. 10.1H).

The temperature of the hypolimnion, when it exists, rose rapidly from 8.4^{o} in November 1992 to 11.8^{o} in March 1993.

10.1.3 Dissolved Oxygen

The rapid hypolimnion temperature rise denotes extensive downward mixing of thermocline water into the hypolimnion. This process, together with the intermittent formation of a hypolimnion means that it would be most difficult to determine meaningful HVOD values for Lake Alexandrina and no DO depletion rates have been calculated for this reason.

The pattern of the DO saturation of surface waters rises steadily from 87% saturation in late summer to about 95% in spring (Fig. 10.1E). A significant ($p<0.01$) decline in DO% saturation of about 2% yr^{-1} was observed from 1992 to 1995 (Fig. 10.1F).

10.2 Trophic State Variables

10.2.1 Chlorophyll *a*

Chla exhibits the pattern of high but variable values in the autumn with low but consistent values in the spring (Fig. 10.2A). No significant change was observed in Chla from 1992 to 1995 (Fig. 10.2B).

10.2.2 Secchi Depth

The annualised pattern for SD was quite strong (Fig. 10.2C; R = 0.75) with low values in the autumn/winter and high values in the spring and is consistent with the observed Chla concentrations. There was a significant ($p<0.01$) change in SD of -0.79 m yr^{-1} which gives a PAC x -1 value of 12% per year of the average SD of 6.54m. SD has a CTS value of +3.

10.2.3 Total Phosphorus

TP tends to be high in autumn and low in spring (Fig. 10.2E) and concentrations increased ($p<0.05$) from 1992 to 1995 (Fig. 10.2F) to give a PAC value of 6.3% yr^{-1}. TP has a CTS value of +1.

Pdiff (Fig. 10.4A,B) shows very similar patterns of change to TP.

10.2.4 Total Nitrogen

TN has high values in the summer-autumn and low values in the winter-spring (Fig. 10.2G) with little change during the period of observation (Fig. 10.2H). Since the NO_3 and NH_4 values are low in comparison to the TN concentrations, TON shows very similar patterns to TN (Figs. 10.4C,D).

10.3 Other Variables

10.3.1 Turbidity

Turbidity shows an increased pattern of change with time in agreement with that shown by SD (Figs. 10.3A, 10.2D) and Fig. 10.3H shows that turbidity is significantly ($p<0.01$) correlated with the inverse of SD (opacity). In fact, the correlation is so strong that it may not be necessary to measure both turbidity and SD in Lake Alexandrina.

10.3.2 pH and Conductivity

Fig. 10.3B shows little change in pH with time but EC has declined significantly (1%) with time at the rate of 1.04 µs/cm yr^{-1} or 1.3% per year of the average value of 84.5 µs/cm (Fig. 10.3C).

10.3.3 Dissolved Nutrients

None of the dissolved nutrients, DRP, NO_3 or NH_4 (Figs. 10.3D,E,F) changed significantly during the period of observation. High concentrations of these nutrients are observed in the bottom waters of the hypolimnion or thermocline on occasion.

10.4 Phytoplankton Phenomena

Only two aggregated samples from Lake Alexandrina were analysed and the results are shown in Table 10.2.

10.5 Conclusions

Stratification and hypolimnetic reoxygenation in Lake Alexandrina are highly variable and HVOD rates are not worth calculating for comparative purposes.

Table 10.0

Lake Alexandrina	Chla	SD	TP	TN	Avs. of PAC, CTS values and of TLx=TLI values	Std. Err.	p-value
PAC (%/yr)	(+1.4)	12.1	6.3	(-2.2)	**5**	2.9	0.25
CTS (units/yr)	0	3	1	0	**1**	0.71	0.21
TLx - 1992	3.49	3.13	3.40	3.37	**3.35**	0.08	
TLx - 1993	2.84	2.70	3.10	3.38	**3.00**	0.15	
TLx - 1994	3.32	3.21	3.22	3.26	**3.25**	0.02	
Avs. of TLc, TLs, TLp, TLn, TLI, p-values	**3.22**	**3.02**	**3.24**	**3.34**	**3.20**	0.07	**0.23**
Time Trend in TLI = -0.05 ± 0.17 units/yr which indicates no trend.							

The table above summarises the results obtained from the monitoring with the average PAC and CTS values being 5 ± 2.9% yr^{-1} and 1 ± 0.71 units respectively. Their average p-value is 0.23 which indicates possible change, which here means the lake is possibly becoming more eutrophic. In this case the TLI trend gives no additional information. The average TLI for Lake Alexandrina is 3.2 ± 0.1 level units and the averages of the TLx indicate that the 4 trophic state variables are in reasonable balance. Certainly, a monitoring programme should be maintained on Lake Alexandrina.

CHAPTER 11

11.0 FRANKTON ARM OF LAKE WAKATIPU

Lake Wakatipu is a huge lake which could only be monitored effectively at high cost. As a possible low cost option, the water leaving the lake was sampled in the Frankton Arm in the expectation that this water would reflect the water quality of the lake as a whole. However, the Frankton Arm is much shallower than the main lake so the water from this arm was isothermal, enabling it to interact with the sediments to a much greater degree than water in the main lake. A diagram of the Frankton Arm with sampling stations is shown in Fig. 11.0. There were 104 samples taken from two depths from two different stations on 26 visits to the lake from November 1992 to June 1995. The lake was sampled for a little over two and a half years and all of the data collected is shown in Table 11.1.

11.1 Physical Variables

There was no strong time trend shown in either lake height or temperature (Figs. 11.1A,B).

11.2 Trophic State Variables

A two and a half year sampling period is not really long enough to establish a trend unless there was a strong change with time. The Chla shows no significant change with time (Fig. 11.2B). There was a decrease ($p<0.01$) in SD (Fig. 11.2D). A closer examination of Fig. 11.2D shows that the SD values in 1994 dropped clearly from the 1993 values and returned to their previous levels in 1995. The SD values dropped from 14.4m in December 1993 to 3.7 in January 1994 with only a small increase in Chla values from 0.2 to 0.55 mg/m^{-3}. It is likely that the observed decrease in SD was related to suspended particles in the water. Unfortunately, TSS and ISS were not measured so that the cause of the decrease in SD cannot be isolated but is probably due to an increase in suspended matter in the water, either from heavy rain or strong winds resuspending bottom material.

TP (Fig. 11.2E,F) shows a weakly significant increase ($p<0.05$). Neither TON nor TN shows a change with time (Figs. 11.2A,B; 11.3 A,B).

11.3 Other Variables

Turbidity (Fig.11.1C) increased sharply in both the near surface and deeper samples in January 1994 showing that the suspended matter was fairly evenly distributed through the water column. The other variables showed some change with time (Figs. 11.1 D - H) but with only a little over two years of data none of the trends can be considered seriously. The monitoring programme would have to be extended in time to determine whether any of the trends were periodic or long term.

11.4 Phytoplankton Phenomena

Three aggregated samples of phytoplankton from Frankton Arm of Lake Wakatipu were anlysed and the data is shown in Table 11.2 with the biovolume of the dominant species shown in Fig. 11.4. There has been no significant changes in species composition with the only consistent change being a small decrease in some chrysophyta *(Dinobryon sp.)*

11.5 Conclusions

The period of observation was relatively brief, nevertheless, the data obtained from the Frankton Arm are numerous enough to establish a baseline for the lake at the time of observation.

Table 11.0

Lake Wakatipu	Chla	SD	TP	TN	Avs. of TLx=TLI values	Std. Err.
TLx - 1992	1.32	2.42	2.02	1.93	1.92	0.23
TLx - 1993	1.20	2.75	2.71	1.95	2.15	0.37
Avs. of TLc, TLs, TLp, TLn, TLI	1.26	2.59	2.37	1.94	2.04	0.20
Time Trend in TLI was not determined.						

The table above shows the TLs value for Frankton Arm to be fairly high as anticipated because of the unstratified nature of the water body The TLc is relatively low as is the case for Lake Taupo. This is probably a result of a lack of calibration data for deep oligotrophic lakes. The TLI of 2.04 ± 0.2 units indicates the Frankton arm to be oligotrophic but it is actually probably microtrophic. It was not possible to establish the cause of the low 1994 SD values. If a further period of observation of the Frankton Arm is established, the recommendation is made that TSS and ISS should be included in the list of variables observed. This recommendation is made because of the isothermal nature of the Frankton Arm, so that it should be sampled like an unstratified water body. Also the main lake should also be sampled for a time to provide a comparison with the Frankton Arm data.

CHAPTER 12

12.0 LAKE TAHAROA

Lake Tahatoa is a relatively deep sand dune lake in a popular recreational reseve and is in pristine condition. The larger basin is about 3 km long and the smaller is about 650m long. There were 94 samplings of Lake Taharoa giving 125 values for epilimnion nutrients. An outline of the lake is shown in Fig. 12.0. This lake is unusual in having two basins separated by a sill 7.0m deep. As the top of the hypolimnion is usually more than 15m deep (Figs. 12.3G,H), the epilimnion waters of the two basins mix but the hypolimnion waters remain separate, and independent HVOD rates have been calculated for each basin.

12.1 Physical Variables

12.1.1 Lake Depth

Fig. 12.1B shows the lake height and hence, lake depth to be highly variable with values in 1992 a metre higher than usual.

12.1.2 Temperature

The variation in annualised epilimnion temperature was from 23^o in February to 12.5^o in July (Fig. 12.1C). There was an increase ($p<0.01$) in temperature of 0.24^{o}C yr^{-1} (Fig. 12.1D).

The hypolimnion temperatures in the two separate basins increased at different rates (Figs. 12.1E,F) notably during the 1992/93 season, indicating differences in vertical mixing rates.

12.1.3 Dissolved Oxygen

The DO disappeared from both basins quite rapidly with anoxic conditions being reached in both basins (Figs. 12.1G,H); longer periods of anoxia existed in the north basin (e.g. February/May 1993).

12.2 Trophic State Variables

12.2.1 Chlorophyll *a*

There is an annual pattern of Chla change from a low of about 0.5 in the summer to a high of 1.5 mg m^{-3} in the winter (Fig. 12.2A). There has been no change of Chla concentration with time (Fig. 12.2B) and the CTS and PAC values for Chla are 0.

12.2.2 Secchi Depth

The SD changes with the Chla being about 11m in the summer and about 8m in the winter (Fig. 12.2C). There was no change in SD with time (Fig. 12.2D) and the CTS and PAC values for SD are 0.

12.2.3 Total Phosphorus

The pattern of annual change in TP is weak (Fig. 12.2E). The average epilimnion value of 4.3 mg m^{-3} TP observed in the lake is remarkably low as is an average value of DRP of 0.4 mg m^{-3}. These concentrations strongly indicate that growth in the lake is phosphorus limited. There is no apparent change in TP concentrations with time (Fig. 12.1F). The CTS and PAC values for TP are 0. The hypolimnetic values for TP remained low except for one occasion in the North Basin (Figs. 12.4A,B) which was largely a result of high DRP (Fig. 12.4D) and indicates that anoxic regeneration of phosphorus can occur.

12.2.4 Total Nitrogen

There is no pattern in the annual TN values (Fig. 12.2G) nor is there any trend in the TN values with time (Fig. 12.2H). The CTS and PAC values for TN are 0.

TON (Fig. 12.5A,B) shows a slightly clearer pattern of increase with time but the increase is not significant.

12.3 Other Variables

12.3.1 Dissolved Reactive Phosphorus

Epilimnetic concentrations of DRP remained very low (Fig. 12.3A) as did hypolimnetic concentrations, except for a high value in the North Basin from a thin layer of anoxic water (26.8m deep) close to the bottom on the 21 February 1995 (Figs.

12.4B,D). This shows that anoxic regeneration of nutrients can occur in this lake, but this occurrence is infrequent at the present time.

12.3.2 Ammonia

The NH_4 levels in the epilimnion remained relatively low (Fig. 12.3B) except for two occasions in May 1993 and 1995 when hypolimnion waters were mixed up into epilimnion waters. Hypolimnetic levels of NH_4 could become quite high toward the end of summer (Figs. 12.4E,F).

12.3.3 Nitrate

NO_3 levels in the epilimnion remained fairly low but were seldom undetectable (Fig. 12.3C). The hypolimnetic concentrations in the South Basin were similar to the epilimnetic levels but those in the North Basin hypolimnion were generally very low because of the low DO levels there (Figs. 12.4G,H).

12.3.4 Turbidity

Turbidity did not change with time (Fig .12.3D) which is in agreement with the observations on SD.

12.3.5 Conductivity and pH

Epilimnetic pH decreased ($p<0.01$) with time (Fig. 12.3E) and conductivity increased ($p<0.01$; Fig. 12.3F) with time, but the reasons for these changes are not known.

12.4 HVOD Rates

Calculation of the HVOD rates for the separate hypolimnia was problematic because of inconsistent data availability. The HVOD and temperature increase rates were found to vary considerably from year to year (Figs. 12.6, 12.7). Fig. 12.3G showed that the north basin had supersaturated conditions at 15m indicating significant growth and oxygen production at that depth. Oxygen production is not easy to observe directly in the hypolimnion because DO saturation levels remain below 100%. However, appreciable DO production can occur in the hypolimnion (Burns 1996). It is very likely that this did happen intermittently in Lake Taharoa because its clear waters permitted light to penetrate into the hypolimnion. Hypolimnetic photosynthesis is probably the cause of the erratic HVOD rates observed, rendering the calculated HVOD rates useless and no PAC or CTS values were calculated for this variable. The North Basin HVOD rate was approximately twice that of the South Basin rate (Tables 12.2, 12.3).

12.5 Phytoplankton Phenomena

Table 12.3 shows the results of analysing three aggregated samples and Fig. 12.10 shows change with time in the dominant species. There was no evidence of a significant change in water quality. However, chrysophta appear to have increased while eugleniodes have declined.

12.6 Conclusions

Changes with time in lake temperature, lake height, pH and EC were observed but no significant changes occurred in the trophic state indicators of Lake Taharoa as shown in the summary table on the next page.

Table 12.0

Lake Taharoa	Chla	SD	TP	TN	Avs. of PAC, CTS values and of TLx=TLI values	Std. Err.	p-values
PAC (%/yr)	(-3.2)	(+1.3)	(-3.7)	(-2)	**0**	0	1
CTS (units/yr)	0	0	0	0	**0**	0	1
TLx - 1992	2.53	2.57	1.98	3.02	**2.53**	0.21	
TLx - 1993	2.27	2.63	2.08	3.20	**2.55**	0.25	
TLx - 1994	2.16	2.78	2.30	2.86	**2.53**	0.17	
TLx - 1995	2.24	2.73	1.98	3.23	**2.54**	0.28	
Avs. of TLc, TLs, TLp, TLn, TLI, p-values	**2.30**	**2.68**	**2.08**	**3.08**	**2.54**	0.10	**1**
Time Trend in TLI = -0.001 ± 0.005 levels/yr. This value indicates no trend.							

Non-significant changes are bracketed.

The table above shows both average PAC and CTS values are 0 ± 0 units indicating no change in the trophic level. The time trend in TLI at 0.001 ± 0.005 also indicates no change. The average TLp value (2.08) is much lower than the TLn value (3.08) indicating that Lake Taharoa is phosphorus limited. The TLI value of 2.5 ± 0.1 units indicates that the lake is oligotrophic.

CHAPTER 13

13.0 LAKE WAIKERE

Lake Waikere is only about 300m from Lake Taharoa and has similar water quality to it. The widest part of the lake is 1 km. Lake Waikere was sampled for less than two years, with 22 samplings at one station. Time trends over such a short period are meaningless but they have been determined on an experimental basis, to compare with those calculated for longer periods. The averaged data on Lake Waikere is shown in Table 13.1. An outline of the lake is shown in Fig. 13.0.

13.1 Physical Variables

13.1.1 Lake Height

Lake height is higher in the spring than the rest of the year by almost 0.5m (Fig. 13.1A).

13.1.2 Temperature

The summer epilimnion annualised temperatures are among the highest recorded in the LMP. The temperature in 1995/96 was lower than in the previous year when seasonally adjusted which (Fig. 13.1D) could indicate the start of a cooling trend. This has not been observed in the trend lines for the longer data collections. The hypolimnion temperatures for the two years were different (Figs. 13.1E,F). The T/DO depth profiles showed a well mixed epilimnion of about 15m with the hypolimnion starting at 20m. Some supersaturation was seen in the thermocline (Figs. 13.4A,B).

13.1.3 Dissolved Oxygen

The DO decreased rapidly after stratification with one or more months of near anoxic conditions (Fig. 13.1G). The DO conditions were low enough to permit NH_4 regeneration but not DRP regeneration (Figs. 13.3F,H).

13.2 Trophic Indicators

13.2.1 Chlorophyll *a*

Chla concentrations increased strongly ($p<0.05$)over the period of observation (Fig. 13.2A) but it is unlikely that Lake Waikere is becoming more eutrophic in the long term with such dramatic changes in Chla levels. This illustrates the danger of short term trends.

13.2.2 Secchi Depth

SD decreased in agreement with the increasing Chla values (Fig. 13.2D).

13.2.3 Total Phosphorus

TP showed no change with time (Fig. 13.2F). The hypolimnion TP concentrations are similar to those of the epilimnion (Figs. 13.2F, 13.3A).

13.2.4 Total Nitrogen

TN shows a strong increase ($p<0.01$) with time (Fig. 13.2H). This could be the reason for the increase in Chla over the period of observation. The hypolimnetic TN values can be higher than the epilimnetic values (Table 13.1, Fig. 13.3B) because of the regeneration of NH_4 toward the end of the stratified season. The differences between TN and TON are interesting. The observed TON values (Fig. 13.5B) vary more regularly than the TN values (Fig. 13.5D). The TON residual values (Fig. 13.5B) give a stronger trend with time than the TN values (Fig. 13.5D).

13.3 Other Variables

13.3.1 Nitrate

NO_3 levels in both epilimnion and hypolimnion remained low (Figs. 13.3C,D).

13.3.2 Ammonia

NH_4 levels in the epilimnion were generally low but higher values occurred in the hypolimnion toward the end of the stratified season (Figs. 13.3E,F).

13.3.3 Dissolved Reactive Phosphorus

DRP values were uniformly low in both the epilimnion and hypolimnion even when there was NH_4 regeneration in the hypolimnion (Figs. 13.1G,H).

13.3.4 Turbidity, pH, Conductivity

Turbidity and EC were variable, with no time trend and with hypolimnetic values in the same range as epilimnetic values. pH was similar except that hypolimnetic values were generally lower than epilimnetic ones, (Figs. 13.4 C-H)

13.4 HVOD Rates

The 1994/95 DO trend lines were not as linear as usually observed (Fig. 13.6). The values for the observed HVOD rates are shown in Table 13.2. As in Lake Taharoa, there is evidence of oxygen production and supersaturation in the thermocline of lake Waikere. There was also probably unobservable DO production in the hypolimnnion, causing the non-linear HVOD rates. Unless the oxygen production is measured and allowed for, the calculated HVOD rates are meaningless.

13.5 Phytoplankton Phenomena

The results of analysing one aggregated sample for phytoplankton biomass are shown in Table 13.3.

13.6 Conclusions

Lake Waikere is an oligotrophic lake. The HVOD rates are considered to be unreliable because of unmeasured DO production. No CTS or PAC values were calculated because the period of observation of two years was too brief for trends to show conclusively. The lake did show an increase in Chla with an accompanying increase in TN.

Table 13.0

Lake Waikere	**Chla**	**SD**	**TP**	**TN**	**Avs. of TLx=TLI values**	**Std. Err.**
TLx - 1994	2.44	2.49	2.13	2.98	**2.51**	0.18
TLx - 1995	3.10	2.89	3.13	3.30	**3.11**	0.08
Avs. of TLc, TLs, TLp, TLn, TLI	**2.77**	**2.69**	**2.63**	**3.14**	**2.81**	**0.11**
Time Trend in TLI was not determined.						

The TLp value (2.63) is much lower than TLn value (3.14) shown in the table above, and indicates phosphorus limitation to growth in the lake. The TLI of 2.8 ± 0.1 units indicates that the lake is oligotrophic with a similar TLI to Lake Taharoa (2.5 ± 0.1).

CHAPTER 14

14.0 LAKE PUPUKE

Lake Pupuke is a lovely lake situated in a suburb of Auckland. It is only 230m from the sea at one point but the water in it is quite fresh. The lake is situated in a former volcanic crater and is relatively deep for its size. From February 1992 to April 1996 there were 104 samplings of Lake Pupuke which yielded 98 values of epilmnion nutrient concentrations and 94 Chla values. There are up to 120 values for hypolimnion variables because on occasion the hypolimnion contained both oxic and anoxic layers and samples were taken from both layers. Fig. 14.0 provides an outline diagram of the lake and sampling stations.

14.1 Physical Variables

14.1.1 Lake Depth

The annualised lake depth varies by about 0.4m from a low of 58.9m in autumn to a high of 59.3m in spring (Fig. 14.1A). There has not been a significant change in lake depth from February 1992 to April 1995 (Fig. 14.1B).

14.1.2 Temperature

The annualised temperature varies from a low of 12^{o}C in July to a high of 23^{o}C in February (Fig. 14.1C). There has been a significant ($p<0.01$) rise in the average epilimnion temperature of 0.33^{o}C yr^{-1} (Fig. 14.1D).

The hypolimnion temperature is remarkably stable showing no rise as the stratified season progresses from October to June (Figs. 14.1E,F). The temperature actually dropped through 1992. This lack of temperature rise indicates no reoxygenation of the hypolimnion by downward mixing and no reoxygenation correction was calculated.

14.1.3 Dissolved Oxygen

Fig. 14.1G shows that the change in the average hypolimnion concentration is fairly slow. However, averaging the hypolimnetic oxygen data distorts the data somewhat because there are two distinct layers of oxygen concentration in the hypolimnion (Fig. 14.4B). The water near the sediments deoxygenates from the sediments upwards while higher oxygen concentrations prevail in the shallower parts of the hypolimnion. This also indicates the lack of hypolimnetic water mixing in this fairly small but deep lake. Fig. 14.1H indicates that the deoxygenation rates can vary, with the 1994/95 rate being greater than the other rates as the slope for this period is steeper and the period of anoxic concentrations is longer.

A DO saturation of 130% was achieved in the spring growth period (September 1995) in epilimnion waters but DO saturation of surface waters can drop to 67% when anoxic bottom waters are mixed upwards.

14.2 Trophic State Variables

14.2.1 Chlorophyll *a*

There is a weak pattern of Chla concentration variation in the year with higher values prevailing in summer and lower values in winter (Fig. 14.2A). Over the period of observation there has been a significant ($p<0.01$) increase in the Chla concentration of 0.65 mg m^{-3} yr^{-1} (Fig. 14.2B) which gives a PAC value of 10.5% yr^{-1} on the average Chla concentration of 6.1 mg m^{-3}. The Chla changes yield a CTS value of +3.

14.2.2 Secchi Depth

The annualised SD values show a fairly consistent pattern of increased depths and thus clearer water in the winter (Fig. 14.2C). Fig. 14.2D shows a significant decrease ($p<0.01$) in SD of 0.49m yr^{-1} from February 1992 to April 1996. This gives a PAC x -1 value of 8.9% per year increase on the average SD of 5.5m. SD changes yield a CTS value of +3.

14.2.3 Total Phosphorus

The annualised TP data show a weak pattern of little change in the year (Fig. 14.2E). There is also no significant change of TP values with time (Fig. 14.2F) yielding CTS and PAC values of 0 for TP. Hypolimnetic TP values can vary from 2 mg Pm^{-3} when there is ample oxygen present to >50 mg P m^{-3} when the water goes anoxic (Fig. 14.3A).

14.2.4 Total Nitrogen

The annualised TN values show very little pattern (Fig. 14.2G) but they do show a significant ($p<0.01$) change with time of a decrease of 19 mg N m^{-3} yr^{-1} (Fig. 14.2H) which gives a PAC value of -7.9% per year on an average TN of 235 mg N m^{-3}. This yields a CTS value of -3.

TON (Fig. 14.5B) shows a decline of 19 mg N m^{-3} yr^{-1}, the same as that of TN. This indicates that the decline in TN is due to a decrease in organic matter in the lake not dissolved nitrogen nutrients.

14.3 Other Variables

14.3.1 Nitrate

Epilimnetic NO_3 has a variable pattern showing occasional high values but also lengthy periods of up to two years with consistently low values (Fig. 14.3C). The hypolimnion showed a similar pattern (Fig. 14.3D).

14.3.2 Ammonia

Ammonia did not show a consistent pattern of change in concentration (Fig. 14.3E). High concentrations were usually observed in the hypolimnion in the anoxic layer (Fig. 14.3F).

14.3.3 Dissolved Reactive Phosphorus

Epilimnetic DRP values were relatively low (Fig. 14.3G), averaging 1.4 mg P m^{-3} (Table 14.1) and did not show a consistent pattern of change. Hypolimnetic concentrations increased during each season, particularly when the waters became anoxic (Fig. 14.3H).

14.3.4 Depth Temperature Oxygen Profiles

The T/DO profiles for Lake Pupuke are most informative. Both Figs. 14.4A,B show small decreases in hypolimnion temperature with depth, indicating the presence of layers in the lake. These layers are clearly shown in the different DO concentrations found with depth. Fig. 14.4A shows the DO concentrations found just after the set-up of stratification. The water below 45m was not reoxygenated as well as that above. The degree of hypolimnetic reoxygenation would vary each year as is indicated in Fig. 14.1G by the spread of values observed for each month.

Fig. 14.4B shows that the thermocline became completely deoxygenated, probably due to organic material settling into that layer, being held there, and then decomposing. Next, there is a layer from 20 to 40 or 50m with higher DO concentrations which loses DO concentration within the layer. The deepest layer loses DO from the bottom upwards. By the end of June the whole hypolimnion is anoxic at which time the stratification begins to break down. The hypolimnion is usually isothermal by August although not completely reoxygenated at that time. Restratification can commence in August.

14.3.5 Turbidity

Fig. 14.4C shows that the epilimnion turbidity did not vary greatly with an average value of 0.6 ± 0.2 ftu (Table 14.1). The hypolimnion values were mostly stable with many unpredictable higher values with an average value of 0.7 ± 1.0 ftu. No trends with time were observed.

14.3.6 pH

Figs. 14.4E,F show the epilimnion annual pattern of higher pH in the summer. The hypolimnion pH decreased during the stratified period. No trends with time were observed.

14.3.7 Conductivity

Figs. 14.4G,H show a slight but significant ($p<0.01$) decrease in EC over the observation period. The epilimnion decrease was 1.7 us/cm yr^{-1} or 0.6% per year on an average value of 289 us/cm. The hypolimnion decrease was 1.2 us/cm yr^{-1} or 0.4% per year on an average value of 291 us/cm.

14.4 DO Depletion Rates

Particular care had to be taken in calculating the HVOD rates. Since the deepest layer of water in the hypolimnion was usually below 3 g DO m^{-3} it could not be included in the calculation. The only water which had DO concentrations above 3 g m^{-3} was that between 20 and 50m from September to December or January. The assumption was made that there was little or no mixing between the different hypolimnetic and thermocline layers so that this layer could be selected and analysed for DO depletion (Fig. 14.6). The results are inconsistent (Fig. 14.6, Table 14.2) so this assumption is not completely valid. The HVOD rates in Lake Pupuke are shown in Table 14.2 and Fig.14.7 for interest only. No CTS or PAC values were given for the HVOD rates.

Fig. 14.7 shows that there was no significant trend in the rates with the simple, observed rates being slightly more consistent than the temperature adjusted rates.

14.5 Phytoplankton Phenomena

Three aggregated samples were analysed for phytoplankton content and the results are shown in Fig. 14.8 and Table 14.3. There has been no significant change in the phytoplankton community with time; the only consistent change being a small decrease in dinoflagellates.

14.6 Conclusions

It definitely appears that phytoplankton density increased because the Chla increase was accompanied by a SD decrease. This change does not appear to be nutrient driven as TON and TN decreased ($p<0.01$), while the TP showed a non-significant decrease. The change in the HVOD rate was not significant but this rate was difficult to measure correctly because of layers existing in the hypolimnion.

The table on the next page shows a summary of the results for the trophic variables for Lake Pupuke.

Table 14.0

Lake Pupuke	Chla	SD	TP	TN	HVOD	Avs. of PAC, CTS values and of TLx=TLI values	Std. Err.	p-values
PAC (%/yr)	10.5	8.9	(-4.0)	-8.1	*	**2.8**	4.3	0.63
CTS (units/yr)	3	3	0	-3	*	**0.75**	1.4	0.56
TLx - 1992	4.34	3.13	3.28	3.74		**3.62**	0.27	
TLx - 1993	3.94	3.21	3.30	3.61		**3.52**	0.16	
TLx - 1994	4.13	3.26	3.21	3.37		**3.50**	0.22	
TLx - 1995	4.44	3.38	3.21	3.47		**3.63**	0.28	
Avs. of TLc, TLs, TLp, TLn, TLI, p-values	**4.21**	**3.25**	**3.25**	**3.55**		**3.56**	0.11	**0.59**
Time Trend in TLI = -0.001 ± 0.04 levels/yr. This value indicates no trend.								

* Non-significant changes are bracketed.

The p-values of the PAC and CTS averages are above 0.3, indicating that no change occurred and the TLI time trend value is in agreement with this result. It would appear that the trophic condition of Lake Pupuke is not changing with time but the significant increase in Chla and decrease in SD indicate that the lake should be watched carefully. The TLI value of 3.6 ± 0.1 means that Lake Pupuke is a mid-range mesotrophic lake.

CHAPTER 15

15.0 LAKE ROTOITI NI

Lake Rotoiti NI lies in the thermally active Rotorua District and has high tourism value. It receives its water from Lake Rotorua and its water quality has declined as a result of the decline in Lake Rotorua water quality (Vincent et al. 1984). The hope is that Lake Rotorua will improve because of the diversion of its sewage input and that this will lead to an improvement in the water quality of Lake Rotoiti NI. The lake is about 11.3 km long. Lake Rotoiti data has been analysed a little differently to the other lakes. Lake Rotoiti has three sampling stations in it because the western end of the lake is shallow, not stratified and receives the inflow from Lake Rotorua and also has the outflow from the lake leaving that basin. The central and eastern parts of the lake are deep and stratified and their water quality is possibly quite different from the western basin. Thus the data from the central and east sampling stations were combined and analysed separately from that of the west sampling station. For some variables the data from the three stations were combined and compared to that from the independent West Station and Central plus East Station analyses. There were 48 Chla and 80 nutrient samples taken from the West Basin and 100 Chla and 132 nutrient samples taken from the Central plus East stations.

Fig. 15.0 shows an outline of the lake and the positions of the sampling stations.

15.1 Physical Variables

The temperature and lake depth data apply to both the West and Central plus East Stations.

15.1.1 Lake Depth

Lake height in Lake Rotoiti is reasonably constant with no more than 50 cm between the highest and lowest levels. The averaged lake height and depth changed from a low of 119.8m in summer to a high of 119.9m in late spring (Fig. 15.1A).

15.1.2 Lake Temperature

The annualised lake temperature varied between a summer high of 20^{o}C and winter low of 10^{o}C (Fig. 15.1C). The deseasonalised data (Temp Residuals) showed a significant increase ($p<0.01$) of 0.22^{o}C per year. The hypolimnetic waters showed an unusually large rise in temperature from 10.5^{o} to 12.5^{o}C (Fig. 15.1E). This is caused partially by geothermal heating (Gibbs 1992). The hypolimnion can set up at quite different temperatures with average temperatures ranging from a low of 11.4^{O}C in 1992/93 to a high of 12.1^{o}C in 1994/95 (Fig. 15.1F). Figs. 15.8A,B show hypolimnetic thermal structures which are more isothermal than those in most lakes. This is due to the geothermal heating of bottom waters.

15.2 Trophic State Variables

15.2.1 Chlorophyll *a*

Figs. 15.2A, 15.3A, 15.4A show the typical central volcanic lakes pattern of a winter Chla maximum. The pattern of Chla change with time is very similar in the shallow and deep basins (Figs. 15.2A, 15.3A) and the whole lake pattern (Fig. 15.4A) is similar to that of both basins. All trends are showing decreased Chla with time, but none of them is significant at the 5% level. The trend shown in Fig. 15.2B is significant at the 10% level. The CTS and PAC value for Chla is 0.

15.2.2 Secchi Depth

The average SD in the west basin (4.3m) is quite different to that of the central plus east basin (6.2m) because of the shallower nature of the west basin causing upward mixing of the sediments. The annualised patterns (Figs. 15.2C, 15.3C) are different as a result. The result of the SD difference is that while both the C+E (Fig. 15.2B) and the W time trends (Fig. 15.3B) show significant ($p<0.01$) increases with time, the combined plot (Fig. 15.4B) does not show a significant trend. This indicates that the SD for the shallow and deep basins of Lake Rotoiti are best analysed separately. The SD is considered to have significantly increased in time and is given a CTS value of -3. This is in agreement with the non-significant trend shown by Chla. The PAC x -1 value is calculated from an increase of 0.20m yr^{-1} in the Central plus East data, giving -3.2% yr^{-1} on an average of 6.2m.

15.2.3 Total Phosphorus

All three of the annualised plots (Figs. 15.2E, 15.3E, 15.4E) of TP show the maximum TP in June/July. This is probably a result of the upward mixing of the enriched, anoxic waters at this time of year.

The change in TP with time is very similar for the West Basin, central plus east and combined time trends (Figs. 15.2F, 15,3F, 15.4F).

All of the time trends show decreases with time but none are significant and the CTS and PAC value for TP is 0.

15.2.4 Pdiff

Pdiff is the difference between TP and DRP and gives an indication of the change in the organic phosphorus in the lake. Pdiff shows a significant ($p<0.01$) decrease in the west, central plus east and combined data plots (Fig. 15.6B,D,F).

15.2.5 Total Nitrogen

TN shows lowest values in the spring after the mid-winter Chla peak (Figs. 15.3G, Figs. 15.4G). None of the time trend plots of TN show any significant trend and the CTS and PAC value for TN is 0.

15.2.6 Total Organic Nitrogen

TON plots show higher values in the late summer and low values in the spring (Figs. 15.5A, 15.5C). Although the TON time trends are not significant, they consistently show larger declines with time than the TN plots (Fig. 15.5B,D,F).

15.3 Other Variables

Since the differences between the western and eastern parts of the lake have been found to be relatively small, only data from the Central and East stations is considered in the remainder of this commentary.

Figs. 15.7A,B show the hypolimnetic concentrations of TP and TN and that the lowest hypolimnetic concentrations of about 20 mg P m^{-3} and 200 mg N m^{-3} are the same as the average epilimnetic concentrations (Figs. 15.2F,H). The hypolimnetic waters increase their concentrations of TP and TN above those of the epilimnion by their increase in DRP (Fig. 15.7H) and NH_4 (Fig. 15.7F) as the stratified season progresses. Hypolimnetic NO_3 increases rapidly (Fig. 15.7D) with the onset of stratification but then decreases to very low levels because of denitrification as the hypolimnetic oxygen levels drop.

The epilmnetic NO_3 and NH_4 levels are generally low with the occasional high concentration in the winter or spring (Figs. 15.7C,E). The DRP shows a pattern of surplus concentration in the mid-winter growth pulse (Fig. 15.7G) with the concentration decreasing after that time. It is probable that the mid-winter growth pulse is a result of the upward mixing of the enriched hypolimnetic waters at that time.

Epilimnetic turbidity (Fig. 15.8C) shows a significant decrease ($p<0.01$) in agreement with the increase shown in the SD (Fig. 15.2D, 15.3D). Hypolimnetic waters also showed a decrease in turbidity (Fig. 15.8D) but the reason for this is not known. EC and pH (Figs. 15.8E,F,G,H) showed no significant change with time.

15.4 HVOD Rates

It is not possible to calculate the amount of reoxygenation of the hypolimnion by downward displacement of oxygen using temperature data because the observed temperature increase was due to both downward mixing of surface waters and geothermal heating. It is not possible to apportion the temperature rise between the two different heating mechanisms.

The observed DO concentration data are shown in Fig. 15.9 and the resultant HVOD rates are shown in Table 15.2 and Fig. 15.10. The temperature adjusted rate has a p-value < 0.05 and thus the results indicate a significant decrease in the HVOD rates adjusted to a constant temperature of 11.0^{o}C. The DO depletion in Lake Rotoiti NI has a CTS value of -1. The decrease of 2.21 mg m^{-3} day^{-1} yr^{-1} on an average HVOD of 62.3 mg m^{-3} day^{-1} yr^{-1} yields a PAC value of -3.5% yr^{-1}.

15.5 Phytoplankton Phenomena

Three aggregated samples were analysed and the results are shown in Table 15.3 and Fig. 15.11.

Over the sampling period Lake Rotoiti showed a general decrease in the numbers of dinoflagellates and cyanobacterial species and an increase in desmids (*Mougeotia* sp., *Staurastrum* sp.) These changes may indicate a small improvement in water quality for this lake.

15.6 Conclusions

This analysis of Lake Rotoiti data shows that the western basin data yield the same indication of change in the lake as the deeper eastern basin, and the Chla, TP and TN data from the two basins can be combined and analysed together. The SD data from the two basins give the same trend with time but cannot be combined because of the difference in the average values.

The results from the trophic state indicators are shown in Table 15.4.

Table 15.4

Variable	Change	CTS Value	PAC Value (% $yr^{-1)}$
Chla	non-significant decrease	0	0
SD	significant increase	-3	-3
TP	non-significant decrease	0	0
TN	non-significant decrease	0	0
HVOD	significant decrease	-3	-3.5
Pdiff	significant decrease	-1	-7.1
TON	non-significant decrease	-	*

Although the results from the four nutrient variables in Table 15.4 are not all statistically significant, they uniformly indicate change to a lower trophic state, in agreement with the significant changes to a lower trophic state indicated by SD and HVOD. Thus, taking into consideration that the decrease in Pdiff is significant and that Pdiff can be considered to be a good surrogate for TP, a CTS value of -1 is given for change in phosphorus concentration.

A summary of the results on Lake Rotoiti is shown in the table on the next page.

Table 15.0

Lake Rotoiti NI	Chla	SD	TP	TN	HVOD	Avs. of PAC, CTS values and of TLx=TLI values	Std. Err.	p-values
PAC (%/yr)	(-4.5)	-3.2	-7.1	-1.1	-3.5	**-2.8**	1.3	0.11
CTS (units/yr)	0	-3	-1	0	-3	**-1.4**	0.67	0.1
TLx - 1992	4.13	3.15	4.03	3.30		**3.65**	0.25	
TLx - 1993	4.03	3.28	4.16	3.29		**3.69**	0.24	
TLx - 1994	3.88	3.09	4.14	3.03		**3.53**	0.28	
TLx - 1995	3.83	3.05	4.02	3.27		**3.55**	0.23	
Avs. of TLc, TLs, TLp, TLn, TLI, p-values	**3.97**	**3.14**	**4.09**	**3.22**		**3.61**	**0.11**	**0.105**
Time Trend in TLI = -0.05 ± 0.03 levels/yr. This trend is confirmed..								

*** Non-significant changes are bracketed.**

The average of the PAC and CTS p-values is 0.105 which is just out of the definite and into the probable change range; so the judgement is that Lake Rotoiti has most probably become less eutrophic. This is confirmed by the TLI trend which shows a small annual improvement of -0.05 ± 0.03 level units yr^{-1} from 1992 to 1996. Lake Rotoiti has a TLI of 3.6 ± 0.1 which indicates that the lake is currently a mid-range mesotrophic lake. The TLn value (3.2) is much lower than the TLp value (4.1) indicating that the lake is nitrogen limited.

CHAPTER 16

16.0 LAKE OKATAINA 1992-1996

Lake Okataina is a lovely lake in a hilly, forested catchment and has high tourism value. It is about 5.8 km long. The lake is unusual in that it has no obvious inflow or outflow and is subject to large changes in water level. The number of epilimnion and hypolimnion samples analysed from February 1992 to June 1996 was 112 and 126 respectively. There were more hypolimnion samples than epilimnion samples because extra samples were taken from the deep, low oxygen layer (Fig. 16.4B) when it was encountered. An outline of the lake with the position of the sampling stations is shown in Fig. 16.0.

16.1 Physical Variables

16.1.1 Lake Height and Depth

Fig. 16.1A shows that the stage height levels of Lake Okataina varied over a 1.8m height during the observation period. This large variation in lake height is possible because the lake has no surface outlet for the lake water. It is possible that the lake has an underwater outlet.

The lake depth has been measured at 76.9m at a stage height of -3.0m. Fig. 16.1B shows that the lake height and depth changed in a fairly regular way, decreasing 1.6m from 77.1m in February 1992 to a low of 75.3m in August 1994 and increasing thereafter to 77m in June 1996.

16.1.2 Temperature

The annualised lake temperatures vary from a high of about 20^{o}C in February to a low of 10^{o}C in September (Fig. 16.1C). The temperature residuals show a significant ($p<0.01$) increase over the measurement period of 0.26^{o}C per year. The hypolimnion temperatures increased steadily during the season (Fig. 16.1E) but were quite different from year to year (Fig. 16.1F).

16.1.3 Dissolved Oxygen (DO)

Epilimnetic DO concentrations were close to saturation during the stratified season and never exhibited more than 5% of super-saturation.

The average hypolimnetic DO concentration changes from an initial stratification value of 10 to 3 gm m^{-3} at the end of stratification in June (Fig. 16.1G). However, Lake Okataina has a near bottom layer of diminished DO concentration (Fig. 16.4B) which has been observed during most summers and has been as low as 0.08 gm m^{-3} (3 May 1993). This layer was never found to be anoxic. Fig. 16.4B shows that supersaturated DO values were obtained at a depth of about 20m, just above the hypolimnion. This deep, supersaturated layer usually only occurs in oligotrophic lakes.

16.2 Trophic State Variables

16.2.1 Chlorophyll *a*

Fig. 16.2A shows a distinct pattern of average low Chla values in summer and higher values in July and August with a range of about 1 mg m^{-3} at any time of the year. The Chla residuals show a significant increase ($p<0.05$) of 0.08 mg m^{-3} per year which gives a PAC value of 4.7% yr^{-1} on an average concentration of 1.63 mg m^{-3}. This gives a CTS value of +1.

In an effort to check whether the near-bottom low oxygen values (Fig. 16.4B) were due to decomposition of organic matter in this layer, Chla samples were taken from the hypolimnion from October 1995 to June 1996 and found to be similar in concentration to that of the epilimnion (Table 16.1). Thus it is highly likely that phytoplankton which has settled onto the bottom, causes the low DO values in the near bottom layer.

16.2.2 Secchi Depth

SD shows the inverse pattern to Chla as expected (Fig. 16.2C), with lowest annualised values in August when the Chla concentration is highest (Fig. 16.2B). Some high values of over 15m depth were observed in the summer. The SD values showed a significant increase ($p<0.0l$) of 0.30m per year and contradicts the observed increase in Chla. This gives a PAC x -1 value of 2.8% per year on an average SD of 10.5m and a CTS value of -3.

16.2.3 Total Phosphorus

The highest surface water TP concentrations were observed in August (Fig. 16.2E) when the enriched hypolimnetic waters were mixed upwards. There was no significant change in the TP concentrations from year to year giving a PAC and CTS value of 0. There is virtually no difference in the patterns shown by Pdiff (Figs. 16.5A,B) and those shown by TP.

16.2.4 Total Nitrogen

TN shows the pattern of being highest in the autumn and winter, and lowest in the late spring (Fig. 16.2G) with a decrease in concentration with time ($p<0.01$) of -4.8 mg N m^{-3} yr^{-1} giving a PAC value of -5.3% yr^{-1} on an average of 91 mg N m^{-3}. TN has a CTS value of -3. TON patterns (Figs. 16.5C,D) are very similar to those of TN.

16.3 Other Variables

Lake Okataina is somewhat distinctive in having a near bottom hypolimnetic layer which has a few gm m^{-3} lower DO concentration than the water 5.0m from the bottom. The chemistry of this layer is also unusual. The plots of the hypolimnetic concentrations of TP (Fig. 16.3A) TN (Fig. 16.3B), NO_3 (Fig. 16.3D), and DRP (Fig. 16.3H) show wide ranges of concentration on the same date. This is because samples were taken from both the low oxygen and higher oxygen layers in the hypolimnion. The nutrient concentration in the low oxygen layer is unusual in that DRP values are found which would suggest presence of anoxic conditions (29 mg P m^{-3} April 1995) but the high nitrate concentration of 57 mg N m^{3} and lower NH_4 concentration of 14 mg N m^{-3} (same sample) indicates oxygenated conditions. It could be that these higher nutrient and lower DO concentrations are the result of oxic decomposition of algal remains on the lake floor in a quiescent layer on the bottom of the lake.

No strong year to year trend is displayed in the epilimnetic or hypolimnetic nutrient variables displayed in Figs. 16.3 A-H.

Examples of the stratified temperature and DO conditions encountered in early and late stratification are shown in Figs. 16.4A,B. Turbidity (Figs. 16.4C,D) shows no clear year to year pattern. Figs. 16.4E,F show that the summer, epilimnetic pH values to be about 8 but the winter isothermal values and the hypolimnetic pH values can be less than 7. Epilimnetic conductivity shows a significant ($p<0.01$) declining year to year trend.

16.4 DO Depletion Rates

It was possible to calculate fairly accurate depletion rates for Lake Okataina because the long stratified period and comparatively low depletion rates permitted use of 8 monthly values from October to May. The plots in Fig. 16.6 all show essentially straight line relationships for the decrease in DO concentrations and increase in temperature during each stratified season. The observed HVOD rates in Table 16.2 show no trend. The rates adjusted for reoxygenation and temperature show a downward trend.

16.5 Phytoplankton Phenomena

Three aggregated samples were analysed and the results are shown in Fig. 16.7 and Table 16.3. The phytoplankton composition of Lake Okataina appears to be stable.

16.6 Conclusions

The results for Lake Okataina show a fairly inconsistent set of changes, particularly the increase in Chla levels being accompanied by a small increase in SD values when the opposite change in SD would be expected. This inconsistency is reflected in the low total CTS value of -5 from 5 variables giving an average CTS value of -1.0. Nitrogen is the limiting nutrient in Lake Okataina and the 5% per year decrease in TN would suggest a decrease in trophic state but a careful inspection of Fig. 16.2H shows that much of the downward trend is due to the high 1992 values as the TN values in the following years were mostly at the same level.

The results obtained in Lake Okataina are summarised in the table below.

Table 16.0

Lake Okataina	Chla	SD	TP	TN	HVOD	Avs. of PAC, CTS values and of TLx=TLI values	Std. Err.	p-values
PAC (%/yr)	4.7	-2.8	(+0.5)	-5.3	0	**-0.68**	1.67	0.3
CTS (units/yr)	1	-3	0	-3	0	**1**	0.84	0.7
TLx - 1993	2.49	2.48	2.66	2.32		**2.49**	0.07	
TLx - 1994	2.80	2.43	2.55	2.17		**2.49**	0.13	
TLx - 1995	2.74	2.35	2.89	2.20		**2.55**	0.16	
TLx - 1996	2.97	2.52	2.69	2.24		**2.60**	0.15	
Avs. of TLc, TLs, TLp, TLn, TLI, p-values	**2.75**	**2.44**	**2.70**	**2.23**		**2.53**	0.24	**0.5**
Time Trend in TLI = 0.04 ± 0.01 levels/yr. This trend is not confirmed.								

*Non-significant changes are bracketed.

The average of the PAC and CTS p-values of 0.5 is in the ‘no change’ range and that is why the weak time trend in the TLI is rejected. The changes in the TLI are the result of a relatively large increase in TLc which is not confirmed by changes in the other variables. The low value of the average TLn indicates that the lake is nitrogen limited. The TLI of 2.5 ± 0.2 indicates that the lake is a mid-range oligotrophic lake.

CHAPTER 17

17.0 LAKE OKAREKA

Lake Okereka has an increasing number of homes which currently dispose of their wastes into septic tanks, built around it. The lake is about 2.8km long and is well used. There were 120 samples taken for epilimnion nutrient analyses and 98 for Chla analysis from Lake Okareka. Ninety samples were taken from the hypolimnion. Fig. 17.0 displays an outline of the lake and the positions of the sampling stations. Station ROKS was replaced with Station ROKC in February 1993 because this was the deepest part in the lake.

17.1 Physical Variables

17.1.1 Lake Depth

Fig. 17.1A shows that there is no annual pattern to changes in lake depth, although Fig. 17.1B shows that there has been an increase ($p<0.01$) in lake depth of about 0.9m from 31.9m in 1993 to 32.8m in 1996.

17.1.2 Temperature

Fig. 17.1C shows the expected annual variation in annualised temperature, from a low of 9^{o}C in July to a high of 21^{o}C in February. There is a year-to-year significant ($p<0.05$) rise in surface temperature of 0.35^{o}C.

Fig. 17.1E shows an almost linear increase in the annual hypolimnion temperature from October to February with a lower rate of temperature increase thereafter. This temperature increase is associated with some reoxygenation of the hypolimnion. Figs. 17.1E,F show that the hypolimnion temperature varies from year to year with the 1994/95 temperatures being noticeably higher than the other years. This does not correspond with higher surface temperatures during this summer but is largely the result of the prevailing temperature at the time of commencement of stratification.

17.1.3 Dissolved Oxygen Concentration

Fig. 17.1G shows that oxygen concentrations decreased in a similar manner each year and that the hypolimnion of Lake Okareka is anoxic for about a month each year from May to June. Lower oxygen levels were experienced sooner in 1992 than the other years (Fig. 17.1H). The 3.0 mg m^{-3} DO concentration is usually reached in February, allowing four months for DO depletion calculations.

17.2 Trophic State Variables (Epilmnion only)

17.2.1 Chlorophylla *a*

Fig. 17.2A shows an annual pattern of a Chla maximum in May and a minimum in October of each year. The average concentration of 2.20 mg m^{-3} indicates that Lake Okareka is a mesotrophic lake bordering on being oligotrophic. The interannual trend line shows a significant increase ($p<0.01$) of 0.23 mg Chla m^{-3} yr^{-1} to give a PAC value of 9.6% per year. This gives Chla a CTS value of +3.

17.2.2 Secchi Depth

SD shows an inverse pattern to Chla (Fig. 17.2C) indicating that the SD is controlled largely by phytoplankton in the water rather than suspended solids. The SD values show a significant ($p<0.01$) decreasing trend of the rather large amount of 0.49m per year. The average SD was 8.62m so the PAC value is 5.7% per year. This is in agreement with the increasing Chla concentrations (Fig. 17.2D) and gives a CTS value of +3 for SD.

17.2.3 Total Phosphorus

The TP pattern of concentration change was in basic agreement with the Chla pattern with the maximum average TP in June of 9.5 mg P m^{-3}, about twice that of 4.7 mg P m^{-3} in the summer (Fig. 17.2E). TP showed a significant ($p<0.05$) increase with time of 0.504 mg P m^{-3} yr^{-1} for a PAC value of 7.1% per year on an average TP concentration of 7.13 mg P m^{-3}. This gives TP a CTS value of +1.

The annualised pattern of Pdiff (Fig. 17.5A) is the same as that of TP (Fig. 17.2E) but the time trend for Pdiff (Fig. 17.5B) is not significant.

17.2.4 Total Nitrogen

Annual changes in TN (Fig. 17.2G) show minima in January and September with maxima in November and February. There is a lot of variability in the TN values as shown in Fig. 17.2H and no pattern of change with time. The CTS and PAC value for TN is 0. The TON patterns (Figs. 17.5C,D) are similar to, but more moderate than, those of TN.

17.3 Other Variables

TP in the hypolimnion showed large changes in concentration increasing toward the end of the stratified period when anoxic conditions began to prevail (Fig. 17.3A). TN concentrations also varied considerably (Fig. 17.3B) but in a more erratic manner.

NO_3 concentrations in the epilimnion were fairly low except for two increases in the midyear (Fig. 17.3C). NO_3 in the hypolimnion was fairly similar and showed highest concentrations in February before the onset of low oxygen conditions in the hypolimnion (Fig. 17.3D).

NH_4 values in the epilimnion were low except in the summer of 1993/94 (Fig. 17.3E) and one value in 1996. Higher values of NH_4 were encountered in the hypolimnion at the end of winter in the anoxic period (Fig. 17.3F).

DRP values in the epilimnion were uniformly low except for one value in 1996 (Fig. 17.3G). Higher values of DRP were found in the hypolimnion during the end of summer low oxygen periods.

Figs. 17.4A,B illustrate the nature of the depth profiles obtained early and late in the stratified season. The DO saturation is near 100% in the surface waters early on in the season but drops as low oxygen water is mixed upward in May.

Turbidity in the hypolimnion shows a significant ($p<0.01$) upward trend (Fig. 17.4D). Epilimnetic pH (Fig. 17.4E) and conductivity show downward trends.

17.4 Dissolved Oxygen Depletion

Fig. 17.6 shows the hypolimnetic oxygen depletion and temperature increase rates for the four summers from October 1992 to June 1996. The temperature increases meant that there was noticeable reoxygenation of the hypolimnion each summer, but reoxygenation rates were variable because the temperature increase rates were variable. Thus the observed DO depletion rates have been adjusted for reoxygenation. Also, since the average hypolimnion temperatures can be quite variable (Fig. 17.1E), the DO depletion rates have been standardised to a hypolimnion temperature of 10^{o}C. The observed and adjusted rates are shown in Table 17.2 and a plot of the adjusted rates with time is shown in Fig 17.7. The temperature adjusted observed rate does not show a significant trend and the PAC and CTS value for HVOD is 0.

17.5 Phytoplankton Phenomena

Three aggregated samples were analysed and the results are shown in Table 17.3 and Fig. 17.8. The phytoplankton composition of Lake Okareka appears to be very stable with the only consistent change being a small increase in desmids.

17.6 Conclusions

The Chla, SD and TP results indicate that the lake is increasing its trophic level while the DO depletion and TN data show no trend. It is probable that there is increased drainage from the septic tanks around the lake causing increased nutrient availability. Since Chla, SD and TP indicate increasing eutrophy, Lake Okareka should be watched carefully in the future.

Table 17.0

Lake Okareka	Chla	SD	TP	TN	HVOD	Avs. of PAC, CTS values and of TLx=TLI values	Std. Err.	p-values
PAC (%/yr)	9.6	5.7	7.1	(-0.3)	(-3.8)	**4.5**	1.93	0.11
CTS (units/yr)	3	3	1	0	0	**1.4**	0.68	0.08
TLx - 1992	2.89	2.56	2.50	3.14		**2.77**	0.15	
TLx - 1993	2.93	2.63	2.55	3.14		**2.81**	0.14	
TLx - 1994	3.30	2.80	2.98	3.11		**3.05**	0.11	
TLx - 1995	3.27	2.88	2.75	3.21		**3.02**	0.13	
Avs. of TLc, TLs, TLp, TLn, TLI, p-values	**3.10**	**2.72**	**2.69**	**3.15**		**2.91**	0.27	**0.095**
Time Trend in TLI = 0.1 ± 0.04 levels/yr. This trend is confirmed.								

*Non-significant changes are bracketed.

The PAC and CTS results for Lake Okataina are shown above and indicate that the lake is becoming more eutrophic. Their average p-value is in the 'definite change' range and the conclusion that the lake is deteriorating is strengthened by the TLI time trend result of a 0.1 ± 0.04 level increase yr^{-1}. Perhaps one of the most telling indications of change of trophic condition is that the TLp and TLn values show that Lake Okereka is phosphorus limited, and it is the only Rotorua District lake to exhibit this condition. This situation could arise from drainage from the septic tanks around the lake loading more soluble nitrogen into the lake than soluble phosphorus. From 1992 to 1996 the TLI of the lake has increased from the 2.8 ± 0.2 to the 3.0 ± 0.1 trophic level so the lake is changing from being oligotrophic to mesotrophic.

CHAPTER 18

18.0 LAKE TARAWERA

Lake Tarawera is an important, good quality Rotorua District lake. It has a hilly, forested catchment and is roughly 9km in diameter. There were 76 samplings of the Lake Tarawera epilimnion and 59 of the hypolimnion with 64 samplings of Chla and SD. The period of monitoring was a little over three years (Table 18.1). Fig. 18.0 shows an outline of the lake and the positions of the sampling stations.

18.1 Physical Variables

18.1.1 Lake Height

Lake height and lake depth varied very little with a decrease of about 20 cm in the late summer (Fig. 18.1A). There was no trend over the period of observation (Fig. 18.1B).

18.1.2 Temperature

The surface waters of the lake showed an annualised temperature variation from 10^{o} to 20^{o}C (Fig 18.1C) and a temperature increase of 0.46^{o}C yr^{-1} ($p<0.01$) The hypolimnion temperatures rose rapidly in the early part of the stratification period especially in the springs of 1992 and 1994 (Figs. 18.1E,F).

The pattern of hypolimnetic temperature change varies from year to year (Fig. 18.1F). The epilimnion is usually about 20m deep with the hypolimnion starting at 40m (Fig. 18.4A,B).

18.1.3 Dissolved Oxygen

Lake Tarawera is stratified for an unusually long time; more than 9 months of the year. The DO concentration decreases almost linearly during that time at a relatively slow rate so that the concentration is still above 7 gm m^{-3} at the time of turnover (Fig. 18.1G). The pattern of DO depletion can vary from year to year at the beginning of the stratified season (Fig. 18.1H) due to the difference in the annual pattern of downward mixing. The DO concentration is fairly uniform vertically but does tend to decrease less than 5m from the bottom (Fig. 18.4A,B).

18.2 Trophic State Variables

18.2.1 Chlorophyll *a*

The lake shows a clear pattern of annual Chla variation with the maximum Chla value occurring just after complete vertical mixing in June (Fig. 18.2A). The winter maximum is almost four times greater than the Chla concentration prevailing during summer. The observed Chla appears to increase with time but the deseasonalised values show very little change with time (Fig 18.2B). The PAC and CTS values for Chla are 0.

18.2.2 Secchi Depth

The annual pattern of SD change seems bimodal with low SD values in the mid-winter corresponding with the Chla maximum and another period of low SD values in December and January (Fig. 18.2C). The SD appears to be increasing with time but not significantly so. The CTS and PAC value for SD is 0.

18.2.3 Total Phosphorus

TP is highest during the unstratified part of the year on average (Fig. 18.2E) but shows a relatively high degree of variability overall (Fig. 18.2F) with no significant trend in time. The CTS and PAC values for TP are 0.

The hypolimnetic TP concentration is relatively low and at a similar level to the epilimnetic concentrations (Fig. 18.3A) indicating no large scale nutrient regeneration. The Pdiff patterns (Fig. 8.5A,B) are very similar to those of TP.

18.2.4 Total Nitrogen

TN shows minimum values from September to November after the period of maximum growth from June to August (Fig. 18.2G). There is presumably a settling out of organic material after the growth pulse. A decrease ($p<0.01$) in TN of -13.2 mg N m^{-3} yr^{-1} was observed (Fig. 18.2H) to give a PAC value of -19.4% yr^{-1} on an average value of 68 mg N m^{-3}. The CTS value for TN is -3.

The hypolimnetic TN concentration (Fig. 18.3B) is highly variable but is generally less than the epilimnetic TN concentration. TON is composed largely of organic nitrogen which is the difference between TN and NH_4 plus NO_3. The values of TON (Figs. 18.5C,D) are very similar to those of TN (Figs. 18.2G,H).

18.3 Other Variables

18.3.1 Nitrate

The epilimnetic NO_3 value is generally very low except for a period in the winter of 1993 (Fig. 18.3C) which led to a decline in NO_3 with time ($p<0.02$)) The hypolimnetic NO_3 concentrations are somewhat lower than the epilimnetic ones (Fig. 18.3D).

18.3.2 Ammonia

The epilimnetic ammonia values are low (Fig. 18.3E) and decreased with time ($p<0.01$) The hypolimnetic values have appeared to decrease with time (Fig. 18.3F).

18.3.3 Dissolved Reactive Phosphorus

Occasional higher values of DRP were observed in the epilimnion (Fig. 18.3G). This, together with the low values of NH_4 and NO_3 indicates N rather than P limitation to growth in Lake Tarawera. Higher values of DRP were observed in the hypolimnion, especially during the 1994/95 summer (Fig. 18.3H).

18.3.4 Turbidity

Turbidity showed high values in both the epilimnion and hypolimnion in January to March 1995 (Figs. 18.4C,D). No decrease in SD was noticed at this time, so the reason for these high values is difficult to understand.

18.3.5 Conductivity and pH

EC and pH are both seen to decrease ($p<0.05$.) in the epilimnion with time by 0.6% and 0.3% respectively and lower values for both were observed in the hypolimnion in the autumn of 1994.

18.4 HVOD Rates

All of the DO and temperature data for the 1992/93 summer (October ’92 to June ’93) are shown in the top diagram of Fig. 18.6 to illustrate the variability in these two parameters in the first 100 days of stratification. Also, there was considerably downward mixing at the end of the season causing the June values to be erratic.

Thus, only the data between January and May of each year (days 120 to 250) were used to determine the HVOD rates for Lake Tarawera (Fig. 18.6).

The results are shown in Table 18.2 and Fig. 18.7. The observed and corrected values for the different seasons were fairly similar and there was no significant trend with time to give a CTS value for HVOD of 0.

18.5 Phytoplankton Phenomena

Three aggregated samples were analysed and the results are shown in Table 18.3 and Fig. 18.8. The phytoplankton composition of Lake Okataina appears to be stable.

18.6 Conclusions

Lake Tarawera is an oligotrophic lake with a low average Chla of 1.1 mg m^{-3}. The trophic state indicators, Chla, SD, TP and HVOD, were variable but showed no change with time but TN decreased with time.

Table 18.0

Lake Tarawera	Chla	SD	TP	TN	HVOD	Avs. of PAC, CTS values and of TLx=TLI values	Std. Err.	p-values
PAC (%/yr)	(+1.5)	(-3.6)	(+5.5)	-19.4	(-2.7)	**-3.9**	3.9	0.38
CTS (units/yr)	0	0	0	-3	0	**-0.6**	-0.6	0.37
TLx - 1993	2.40	2.68	3.00	2.07		**2.54**	0.20	
TLx - 1994	2.35	2.53	3.39	2.07		**2.59**	0.28	
Avs. of TLc, TLs, TLp, TLn, TLI, p-values	**2.38**	**2.61**	**3.20**	**2.07**		**2.56**	0.16	**0.38**

*Non-significant changes are bracketed.

The monitoring results on Lake Tarawera are shown in the table above and the average of the PAC and CTS p-values (0.38) indicates no change in the lake. There was not enough data for determination of a TLI trend, but the average TLI for the period was determined to be 2.6 ± 0.2, indicating that Tarawera is a mid-range oligotrophic lake. The difference between the TLp value of 3.2 and the TLn value of 2.1 indicates that the lake is definitely nitrogen limited.

CHAPTER 19

19.0 LAKE ROTOKAKAHI 1992-1996

Lake Rotokakahi has a catchment which is forested and largely undisturbed and was included in the LMP set of lakes as a reference lake which, hopefully, had unchanging water quality. The lake is about 3.5 km long. From December 1992 to June 1996, 107 epilimnion and isothermal samples were taken from Lake Rotokakahi of which 85 were analysed for Chla. There were 70 hypolimnion samples taken. Fig. 19.0 shows an outline of Lake Rotokakahi and the location of the sampling stations.

19.1 Physical Variables

19.1.1 Lake Depth

Lake depth shows an annualised variation of 0.11m from 30.43m in the summer to 30.54 in the late winter (Fig. 19.1A). The lake height or depth has shown a small but significant ($p<0.01$) increase of 3.6 cm yr^{-1} (Fig. 19.1B).

19.1.2 Temperature

The lake temperature varies from a summer temperature of 21^o to a winter value of 9^{o}C (Fig. 19.1C). There has been a significant ($p<0.01$) increase of surface temperatures of 0.35^{o}C yr^{-1} (Fig. 19.1D). The hypolimnion temperature increases in a linear fashion from 9.5^o to 11^{o}C from September to January when the temperature increase diminishes (Fig. 19.1E). Fig. 19.1F shows that the hypolimnion can set up at quite different temperatures. The 1994/95 summer temperature setting up at 1.5^{o}C above the 1993/94 and 1995/96 temperatures of 9.5^{o}C.

19.1.3 Dissolved Oxygen

Fig. 19.1G shows that the hypolimnetic DO declines in concentration in a near linear manner and reaches the 3.0 g m^{-3} concentration at about the start of February. Below 3.0 g m^{-3} DO, the HVOD rate becomes affected by the concentration, giving about four months of possible oxygen depletion rate data. The hypolimnion can be anoxic from March to early May, when upward mixing occurs.

19.2 Trophic State Variables

19.2.1 Chlorophyll *a*

Chla concentrations are highest in May just after the enriched hypolimnion waters have been mixed up into the surface waters, with the lowest concentrations observed in the late spring (Fig. 19.2A). Fig. 19.2B shows a significant ($p<0.01$) upward trend for the deseasonalised Chla values (residuals). The change is 0.39 mg Chla m^{-3} per year which gives a PAC value of 15% yr^{-1} of the average value of 2.6 mg Chla m^{-3}. This also gives a CTS value of +3.

19.2.2 Secchi Depth

The changes in the annual pattern of SD are an inverse of the annual pattern of the Chla concentrations (Figs. 19.2C, 19.2A). This indicates that there is little influence of suspended silt in the lake and most of the suspended material is organic in origin. However, there is no significant time trend in SD (Fig. 19.2D) and this gives a CTS value of 0.

19.2.3 Total Phosphorus

The highest TP surface concentrations are usually found in the winter (Fig. 19.2E) but no trend over time is found in these values (Fig. 19.2F). The hypolimnetic TP varied from lows of 4 mg P m^{-3} at the beginning of the season to highs of about 40 mg P m^{-3} under oxic conditions and 80 mg P m^{-3} under anoxic conditions (Fig. 19.3A). The patterns shown by Pdiff (Fig. 19.5A,B) are very similar to those shown by epilimnetic TP (Figs. 19.2E,F) with no trends with time showing with either variable. TP is assigned a CTS and PAC value of 0.

19.2.4 Total Nitrogen

TN concentrations are usually highest at about the same time of year as Chla (Figs. 19.2G,A). The TON annualised pattern (Fig. 19.5C) is different to that of TN (Fig. 19.2G) but both TN (Fig. 19.2H) and TON (Fig. 19.5D) show no trend with time. TN is assigned a CTS and PAC value of 0.

Hypolimnetic TN (Fig. 19.3B) can vary from a value of <100 to a high of >375 mg N m^{-3} as the stratified season progresses and anoxic conditions are encountered.

19.3 Other Variables

Surface NO_3 concentrations are usually less than 4 mg N m^{-3} under stratified conditions but greater than that when hypolimnetic waters mix upwards (Fig. 19.3C). Surface NH_4 values are usually lower than 20 mg N m^{-3} except during the unstratified period when they can be considerably higher (Fig. 19.3E). This is probably due to the upward mixing of the hypolimnetic water (Fig. 19.3F).

DRP surface values are consistently low (Fig. 19.3G) indicating some level of phosphorus limitation. The hypolimnetic values vary considerably rising from about 1 mg P m^{-3} at the beginning of the stratified period to ±30 mg P m^{-3} during anoxia.

Figs. 19.4A,B show that the epilimnion extended to a depth of about 10m, the thermocline from 10 to 20m and the hypolimnion from 20m to the bottom. There was no significant supersaturation in the lake.

Turbidity showed some irregular high values in the epilimnion (Fig. 19.4C) and a pattern of higher values in the midsummer in the hypolimnion (Fig. 19.4D).

The values of pH in the epilimnion were unpredictable but decreased steadily in the hypolimnion as the DO was converted into CO_2 (Figs. 19.4E,F).

The pattern of change in conductivity (Figs. 19.4G,H) was unpredictable.

19.4 HVOD Rates

The hypolimnetic DO depletion and temperature increase rates were linear (Fig. 19.6). These results are summarised in Table 19.2. The level of reoxygenation in Lake Rotokakahi is high, being about 25% of the reoxygenated rate. All the rates decline with time with the observed and temperature adjusted observed rate having a p-value of < 0.2 (Fig. 19.7). The rates were declining at 2.4 mg m^{-3} day $^{-1}$ per year to give a PAC value of -3.4% yr^{-1} of the average rate 69.2 mg m^{-3} day. This also gives a CTS value of -1 for the HVOD rates. In the case of Lake Rotokakahi the reoxygenation correction caused a decrease in the correlation of DO depletion with time.

19.5 Phytoplankton Phenomena

Three aggregated samples for Lake Rotokakahi were analysed and the results are shown in Fig. 19.8 and Table 19.3.

There was no evidence of a significant change in water quality, however desmids and diatoms appear to be increasing while dinoflagellate and cyanobacteria species appear to have declined.

19.6 Conclusions

No unusual processes were observed to be present in Lake Rotokakahi. The table on the next page summarises the changes observed in the trophic state variables.

Table 19.0

Lake Rotokakahi	Chla	SD	TP	TN	HVOD	Avs. of PAC, CTS values and of TLx=TLI values	Std. Err.	p-values
PAC (%/yr)	15	(-1.4)	(+0.7)	(-1.5)	-3.4	**2.3**	3.2	0.59
CTS (units/yr)	3	0	0	0	-1	**0.4**	2.3	0.51
TLx - 1993	3.03	3.03	3.30	3.11		**3.12**	0.06	
TLx - 1994	3.10	2.88	3.63	2.88		**3.12**	0.18	
TLx - 1995	3.24	2.92	3.54	3.00		**3.17**	0.14	
Avs. of TLc, TLs, TLp, TLn, TLI, p-values	**3.12**	**2.94**	**3.49**	**3.00**		**3.14**	0.07	**0.54**
Time Trend in TLI = -0.03 ± 0.14 levels/yr. No trend.								

*Non-significant changes are bracketed.

Only Chla and DO Depletion Rate (HVOD) showed any significant trends with time but they gave contradictory signals, with the Chla indicating change to more eutrophic conditions and the HVOD to less eutrophic conditions. The high PAC and CTS p-value average (0.54) indicates no change in the lake and this is confirmed by the TLI trend which is indeterminate. A comparison of the TLn and TLp values indicates that Lake Rotokakahi was nitrogen limited. It has a TLI of 3.1 ± 0.1, so it is a low-range mesotrophic lake.

CHAPTER 20

20.0 LAKE ROTOMA

Lake Rotoma was added to the list of monitored lakes after the programme had commenced. Funding difficulties prevented the continued monitoring of this lake and it was discontinued after 8 months. An outline of the lake with the position of the sampling stations marked is shown in Fig. 20.0. The lake is about 5.5 km long.

The full set of water quality data which was collected is shown in Table 20.1. Since only 8 months of data was collected, no annualised or time trend plots of the data were produced. However, since the data collection period spanned seven months of the stratified period, it was possible to calculate HVOD rates for the 1992/93 season as shown in Fig. 20.2. Fig. 20.1 shows that the lake was strongly stratified in February 1993 with DO concentrations that changed relatively little with depth.

The calculated HVOD rates are low with relatively little reoxygenation (Table 20.2). This information, together with that shown in Table 20.1 for Chla and nutrient concentrations, indicates that Lake Rotoma is a relatively deep, stable, oligotrophic lake.

No TLI values were calculated for the lake because a complete years data was not available.

CHAPTER 21

21.0 LAKE OKARO

Lake Okaro is a small lake of about 740m in diameter(Fig. 21.0), and is highly eutrophic. Since data and interpretation of findings on this lake are available in the literature (Forsyth et al. 1988) and a shortage of funding existed, the decision was taken to stop monitoring this lake after only 10 months of data was available (Table 21.1). The most interesting aspect of this lake was its rapid deoxygenation, becoming anoxic after two months of stratification.

The complete set of water quality data collected on Lake Okaro is shown in Table 1.4 and averages of the collected data are shown in Table 21.1.

CHAPTER 22

22.0 LAKE TUTIRA

Lake Tutira is in a pastoral catchment which is subject to landslips. It has its inflow very close to its outflow and this probably increases the residence time of the majority of the water in the lake which is about 2.4 km long. There were 105 samples taken from the epilimnion of Lake Tutira which yielded 95 Chla results. There were 110 hypolimnion samples. Although there were less hypolimnion sampling dates, more hypolimnion samples were taken because one sample was often taken from the upper oxygenated hypolimnion and the other from the deeper anoxic part of the hypolimnion. An outline of the lake is shown in Fig. 22.0.

22.1 Physical Variables

22.1.1 Lake Height and Depth

The average lake depth was 40m and showed very little variation with a standard deviation of 0.22m. Also, there was no significant trend from 1992 to 1996, (Figs. 22.1A,B).

22.1.2 Lake Temperature

The annualised lake surface waters reached 22°C in January and dropped to 9.5°C in July and August on average (Fig. 22.1C). There was a significant ($p<0.01$) rise in temperature of the lake from February 1992 to June 1996 of 0.39°C per year (Fig. 22.1D).

The hypolimnion is relatively persistent, existing from September to July, although it begins eroding downward in April. The hypolimnion temperatures could be quite variable with the 1994/95 temperature obviously warmer than the preceding two years (Fig. 22.1F). The standard hypolimnion temperature for oxygen depletion calculations is taken as 10.00°C.

22.1.3 Dissolved Oxygen

The main feature shown by Figs. 22.1G,H is that the hypolimnion has become anoxic by April each year and continues in that state for about two months more. Fig. 22.1H shows that the deoxygenation rate is linear except that reoxygenation events can be seen in the data.

22.2 Trophic State Variables

22.2.1 Chlorophyll a

Chla shows a maximum in March with some exceptionally high values in April (Fig. 22.2A). This is associated with high TP values at this time (Fig. 22.2E). The Chla maximum is not marked but algal blooms occurred in the late summer of 1992/93 and 1994/95. There was no significant trend in Chla with time. The CTS and PAC value for Chla is 0.

22.2.2 Secchi Depth

SD does not show a marked change during the year (Fig. 22.2C) and there is no significant trend with time (Fig. 22.2D). The CTS and PAC value for SD is 0.

22.2.3 Total Phosphorus

TP shows a definite maximum in late summer (March and April) and a minimum in late winter (August and September). The source of the late summer TP is of interest. It could come from heavy rains at this time bringing in phosphorus from the catchment but this would usually mean that SD would also diminish at this time which didn't happen (Fig. 22.2C). It could also result from upward mixing of enriched hypolimnion waters which existed in March (values of 30 mg P m^{-3}) and this appears to be the most likely mechanism. There was no significant trend of TP with time and it has a CTS and PAC value of 0.

Hypolimnetic TP shows high values at the end of the stratified period every year (Fig. 22.4A).

Pdiff (Fig. 22.3A) shows an annualised pattern which is very similar to that of TP. The trend of Pdiff with time (Fig. 22.4B) is stronger than that of TP (Fig. 22.2F) but is still not significant.

22.2.4 Nitrogen

TN shows an indefinite annual pattern except for some lower values in the late winter and spring (Fig. 22.2G). TN has no significant trend with time (Fig. 22.2H) and has a CTS and PAC value of 0.

The TON annualised pattern (Fig. 22.3C) is much more regular than that of TN, showing a definite set of lower values in the spring. This does not, however, enable the time trend plot (Fig. 22.3D) to show significant decrease with time.

Hypolimnetic TN (Fig. 22.4B) shows a high degree of variability.

22.3 Other Variables

Surface NO_3 is briefly high in the middle of the winter, after which it is taken up in the spring (Fig. 22.4C). The hypolimnetic NO_3 is highest around December after which it is denitrified and its concentration diminishes (Fig. 22.4D).

Surface NH_4 is also high at the time the NO_3 is high (Fig. 22.3E) but the hypolimnetic NH_4 levels often increase as the NO_3 levels decrease (Fig. 22.4F).

Surface DRP values are high in mid-winter when the hypolimnetic waters mix upwards (Fig. 22.4G). High hypolimnetic concentrations of DRP can be seen in Fig. 22.4H at the end of each stratified season.

Fig. 22.5A shows that the DO concentration drops near the sediment. The DO concentration near the sediment reaches zero in February. This low concentration works its way up the hypolimnetic water column so that all the hypolimnion is anoxic in March, when the temp/DO profile becomes similar to that shown in Fig. 22.5B.

Turbidity doesn't show any trend except for some occasional high values (Figs. 22.5C,D) which are not easily explained.

Fig. 22.5E shows some high summer pH values of >9.0 which decrease to mid-winter low values. Fig. 22.5F shows hypolimnetic values decreasing as the stratified season progresses, reflecting the conversion of O_2 into CO_2.

Fig. 22.5G shows that there was a significant ($p<0.01$) increase in conductivity. The reason for this is not known.

22.4 DO Depletion Rates

Fig. 22.6 shows that linear DO depletion rates can be obtained in the early stratified season. Table 22.2 and Fig. 22.7 show that the observed HVOD rates were similar and showed an improved correlation when adjusted for temperature. However, the reoxygenation correction for 1994/95 was very large due to the high rate of temperature increase in that season. It is so different from the other rates of temperature increase that it may be suspect. A possible cause for this could be that the temperature probe may have been recalibrated during the season. This illustrates the need for accurate temperature data at all times. There is no significant trend in the DO depletion data (Fig. 22.7) and the CTS and PAC values are 0.

22.5 Phytoplankton Phenomena

Three aggregated samples from Lake Tutira were analysed for phytoplankton content and the results are shown in Table 22.3 and Fig. 22.8.

Over the sampling period Lake Tutira has shown a general decrease in the numbers of dinoflagellates and an increase in cyanobacterial species *(Anabeana*, *Osillatoria* and *Microcyctis* sp.). These changes indicate a small decrease in water quality for this lake.

22.6 Conclusions

Lake Tutira has shown a temperature increase with time as have the other lakes investigated.

Table 22.0

Lake Tutira	Chla	SD	TP	TN	HVOD	Avs. of PAC, CTS values and of TLx=TLI values	Std. Err.	p-values
PAC (%/yr)	(+2.2)	(-3.3)	(+0.4)	(+0)	(-4.2)	**0**	0	1
CTS (units/yr)	0	0	0	0	0	**0**	0	1
TLx - 1992	3.85	3.78	3.83	3.92		**3.84**	0.03	
TLx - 1993	4.10	3.79	3.83	3.92		**3.91**	0.07	
TLx - 1994	4.00	3.81	3.69	3.76		**3.81**	0.07	
TLx - 1995	3.66	3.63	3.73	3.91		**3.73**	0.06	
Avs. of TLc, TLs, TLp, TLn, TLI, p-values	**3.90**	**3.75**	**3.77**	**3.87**		**3.82**	0.03	**1**
Time Trend in TLI = -0.04 ± 0.03 levels/yr. This trend is unconfirmed.								

*Non-significant changes are bracketed.

The results of measuring the trophic variables in Lake Tutira are shown in the table above. None of the variables showed any trend with time and thus yield the same average values for both the CTS and PAC indicators, namely 0±0. The unconfirmed time trend in the TLI of -0.04 ± 0.03 infers 'no change'. Thus all the trophic level indicators give the result that Lake Tutira did not change between 1992 and 1996. The lake has a TLI of 3.8 ± 0 which indicates that the lake is mesotrophic but close to the eutrophic level, which would account for the heavy algal blooms occasionally found in the lake.

CHAPTER 23

23.0 LAKE ROTOITI SI

Lake Rotoiti SI was included in the LMO as an example of a South Island lake with a forested catchment. It is about 7.8 km long. From February 1992 to June 1994 there were 64 samplings of the surface waters and 37 samplings of the hypolimnion waters of the lake carried out. Fig.23.0 shows an outline of Lake Rotoiti SI and the position of the sampling stations. The data collection on this proceded for only 2 years 4 months. As three years of data is considered necessary to establish valid trends, none of the trends shown here are considered meaningful.

23.1 Physical Variables

23.1.1 Lake Depth

Fig. 23.1A shows lake depth to be about 0.3m higher in the summer than in the winter, with a trend ($p<0.05$) to increasing depth with time (Fig. 23.1B).

23.1.2 Temperature

The annualised temperature plot, Fig. 23.1C, shows a relatively cold lake with a summer high temperature of only 15.5^{o}C and a winter low of about 6.0^{o}C. Fig. 23.1D shows a trend ($p<0.05$.) to higher epilimnion temperatures of 0.41^{o}C yr^{-1}. Fig. 23.1F shows that the hypolimnion temperatures can vary from year to year. There is a possibility that some of this difference can be attributed to slightly different calibration of the temperature probe from year to year.

23.1.3 Dissolved Oxygen

There was some slight supersaturation of DO in the epilimnion only in December and January 1994. Fig. 23.1G shows that hypolimnetic DO concentration decreased in an almost linear fashion from November to June but Fig. 23.1H shows that decrease each year was not apparently smooth. This is possible due to measurement error, because the change in DO concentration each month was very slight. In fact, over the 7 or 8 months of stratification, the DO concentration dropped only from an average of 10.7 to 8.5 g m^{-3} (Fig. 23.1G). This small rate of monthly change in DO means that the DO probe had to be very well calibrated before each measurement was taken. This may not have always been the case.

23.1.4 Temperature/DO Profiles

Figs. 23.5A,B show the early and late summer thermal structure of Lake Rotoiti SI to be a shallow epilimnion to about 10m with the hypolimnion below 40m. The hypolimnetic DO concentrations are uniformly high with a slight decrease sometimes observed near the bottom.

23.2 Trophic State Variables

23.2.1 Chlorophyll *a*

Fig. 23.2A shows the annualised Chla to be about 0.5mg m^{-3} for most of the year with an increase in the spring to about 2 mg m^{-3}. There was a significant decrease ($p<0.01$) in Chla from 1992 to 1994 of 0.32 mg m^{-3} yr^{-1} or 30% per year of the average value of 1.08 mg m^{-3}.

23.2.2 Secchi Depth

SD was lowest in summer and increased markedly with the onset of winter (Fig. 23.2C). Fig. 23.2D shows a significant ($p<0.01$) increase of SD with time in agreement with the observed decrease in Chla. The increase in SD is 1.35 m yr^{-1} or 15% per year of the average SD of 9.2m.

23.2.3 Total Phosphorus

TP concentrations did not change meaningfully during the year (Fig. 23.2E), but there was an increase in TP concentration with time ($p<0.05$) of 1.35 mg P m^{-3} yr-1 which is about 33% of the average TP of 4.1 mg P m^{-3}.

The Pdiff diagrams (Figs. 23.3A,B) are very similar to those of TP because of relatively little change in DRP (Fig. 23.4A).

Hypolimnetic TP concentrations (Fig. 23.4A) did not show much change and were very similar to the epilimnion values.

23.2.4 Total Nitrogen

TN changed in a bimodal manner with highest concentrations in autumn and spring (Fig. 23.2G). There was no apparent change in TN concentration with time. Hypolimnetic TN concentrations did not show any particular pattern of change (Fig.

23.4B). The TON patterns (Figs. 23.3C,D) were similar to the TN patterns in spite of the variable NO_3 and NH_4 values (Figs. 23.4C,E).

23.3 Other Variables

23.3.1 Nitrate

Epilimnetic NO_3 values were generally low with some unpredictably high values in mid-year (Fig. 23.4C). Hypolimnetic NO_3 values showed increasing concentration as the stratified season proceeded (Fig. 23.4D).

23.3.2 Ammonia

Both the epilimnetic and hypolimnetic ammonia concentrations showed significant ($p<0.01$) increases with time. This may be due to the decreased phytoplankton growth during this period, taking up less nitrogen nutrients (Figs. 23.4E,F).

23.3.3 Dissolved Reactive Phosphorus

DRP of both epilimnion and hypolimnion remained at very low concentrations (Figs. 23.4G,H).

23.3.4 Turbidity

Turbidity increased significantly ($p<0.01$) in both the epilimnion and hypolimnion (Figs. 23.5C,D) in contradiction to the changes in Chla and SD. This is not easy to understand.

23.3.5 Conductivity and pH

Neither pH or EC showed much change from 1992 to 1994 (Figs. 23.5E,F,G,H).

23.4 HVOD Rates

Fig. 23.6 shows the temperature increase and observed HVOD rates calculated for 1991/92, 1992/93 and 1993/94. The HVOD rates for 1993/94 were regarded as being invalid because of excessive variability in the DO data. Table 23.2 shows the HVOD rates calculated from the available data. It is estimated that downward mixing contributed about 10% of oxygen taken up in the hypolimnion. Both the observed and calculated rates were very low. It was not possible to determine a time trend with only HVOD rates for two years.

23.5 Phytoplankton Phenomena

One aggregated sample was analysed for phytoplankton species and biomass and the results are shown in Table 23.3.

23.6 Conclusions

Since the data collection on Lake Rotoiti proceeded for only a little over two years, the changes with time are not reliable even if statistically significant. The variability in the data in Fig. 23.6 shows the need for very careful calibration of both temperature and DO probes because of the very small change in these variables with time in Lake Rotoiti SI.

Table 23.0

Lake Rotoiti SI	Chla	SD	TP	TN	HVOD	Avs. of TLx=TLI values	Std. Err.
TLx - 1993	2.47	2.89	1.94	1.63	*	2.23	0.28
TLx - 1994	2.13	2.57	2.08	1.76	*	2.13	0.17
Avs. of TLc, TLs, TLp, TLn, TLI.	2.30	2.73	2.01	1.70		2.18	0.15
Time Trend in TLI was not determined.							

The table above summarises the results of monitoring the trophic state variables in Lake Rotoiti SI. The lake has a TLI of 2.2 ± 0.2 units, indicating that it is a 'low end of the range' oligotrophic lake. The TLn is lower than the other TLx variables, indicating that the lake is relatively deficient in nitrogen compared to most NZ lakes. The TLs is higher than the other TLx, which is unusual for a deeper lake. There could be some very fine inorganic or organic material entering the lake.

CHAPTER 24

24.0 LAKE BRUNNER

Lake Brunner was included in the LMP as an example of a coloured beech forest lake and because of its high fishery and tourist value. It is a large lake being about 9.1 km long and 6.4 km wide. There were 66 samplings of the Lake Brunner epilimnion with 59 samples analysed for Chla. There were 48 samples taken from the hypolimnion. An outline of the lake is shown in Fig. 24.0.

24.1 Physical Variables

24.1.1 Lake Depth

Observed lake depth showed a fairly large variation between a maximum of 111.0 and a minimum of 108.0m, with a slight tendency to greater depths in the winter (Fig. 24.1A). There was a significant ($p<0.01$) increase in lake depth. The lake depth was at a maximum in 1994.

24.1.2 Lake Temperature

February is consistently the month with the warmest surface temperatures in the 17-18^{o}C range. The lowest temperatures are in July-September at about 8.5^{o}C (Fig. 24.1C). There was no significant change in the temperature with time (Fig. 24.1D). Average hypolimnion temperatures increased from October to May and then decreased as thermocline water mixed downward into the hypolimnion in late May and June (Fig. 24.1E). Fig. 24.1F shows that the hypolimnion of 1993/94 was warmer than the other years.

24.1.3 Dissolved Oxygen

Fig. 24.1G shows that Lake Brunner is stratified for the unusually long period of ten months from September to June but nevertheless maintains oxygen concentrations mostly above 7 g m^{-3}.

24.2 Trophic State Variables

24.2.1 Chlorophyll *a*

Fig. 24.2A shows that the highest Chla concentrations are found in the late summer and autumn when the lake is still stably stratified. The reason for this is not immediately obvious. Fig. 24.2B shows that the Chla has significantly ($p<0.01$) increased with time, at the rate of 0.35 mg Chla m^{-3} yr^{-1} which gives a PAC value of 32% per year on the average Chla value of 1.1 mg m^{-3}. It is possible that this is a short term variation which would disappear in the long term. Nevertheless, Chla has a CTS score of +3.

24.2.2 Secchi Depth

Fig. 24.2C shows higher SD values in late summer when lower values might be expected because of the higher Chla concentrations. Fig. 24.2D, however, does show the SD values decreasing significantly ($p<0.01$) with time as could be expected with the increasing Chla levels. The decrease is 0.44 m yr^{-1} which gives a PAC x -1 value of 7% of the average value of 6.2m. The changes in SD yield a CTS score of +3.

24.2.3 Total Phosphorus

The epilimnetic TP concentrations increased but not significantly so from year to year (Fig. 24.2F), neither did the hypolimnetic concentrations (Fig. 24.4A). The Pdiff patterns (Figs. 24.3A,B) are almost identical to the TP patterns because of the low DRP values (Fig.24.4G). TP yields a CTS and PAC value of 0.

24.2.4 Total Nitrogen

TN shows a non-significant pattern of change from year to year (Figs. 24.2G,H). The TON plot (Fig. 24.3D) shows a significant ($p<0.05$) increase in TON in agreement with the observed increase in Chla. TN yields CTS and PAC values of 0.

24.3 Other Variables

NO_3 shows a pattern of decreasing values from above 100 mg N m^{-3} in the winter to less than 40 mg N m^{-3} in the summer with 1995 values dropping to 5 mg N m^{-3} (Fig. 24.4C). This could be a result of converting the nitrate into organic biomass as indicated by the increase in TON with time. NO_3 values in the hypolimnion remained high (Fig. 24.4D).

Ammonia concentrations in both epilimnion and hypolimnion showed no pattern (Figs. 24.4E,F).

The DRP concentrations in the epilimnion are extremely low (Fig. 24.4G) and indicate that phytoplankton growth in the lake is probably phosphorus limited. The increasing trend in P values in the hypolimnion (Fig. 24.4H) is probably spurious and results from a few high values in 1996.

Although not clearly shown in Figs. 24.5A,B the epilimnion depth usually extended to 20m while the hypolimnion usually commenced at 40m. Slightly lower oxygen concentrations prevailed close to the bottom.

The turbidity data does not show any particular pattern (Figs. 24.5C,D) except that on occasion surprisingly high values can be obtained.

Figs. 24.5E,F do not show that pH exhibited any strong patterns of behaviour. Both surface and bottom waters showed a pattern of decreasing conductivity (Figs. 24.5G,H) with the hypolimnetic trend being significant ($p<0.05$).

24.4 HVOD Rates

The long stratified period yielded near linear DO depletion rates but the hypolimnetic warming rates were more erratic (Fig. 24.6). The results in Table 24.2 and Fig. 24.7 show that the most consistent rates were the simple observed rates. The temperature adjustments worsened the correlation of HVOD rates slightly, but the reoxygenation correction deteriorated the correlation quite markedly. The year to year pattern of change was not significant and the CTS and PAC values for HVOD rates are zero.

24.5 Phytoplankton Phenomena

Two aggregated samples of Lake Brunner phytoplankton were analysed and the results are shown in Table 24.3.

24.6 Conclusions

Three years of data were available for Lake Brunner and the trends observed may be short term, ie the trends observed relate possibly to weather conditions and could easily be reversed in the following three years. The trend of increasing Chla was confirmed by a corresponding trend of decreasing SD values.

Table 24.0

Lake Brunner	Chla	SD	TP	TN	HVOD	Avs. of PAC, CTS values and of TLx=TLI values	Std. Err.	p-values
PAC (%/yr)	32.2	3	(+3.5)	(+1.9)	(-3.7)	**7**	6.3	0.18
CTS (units/yr)	3	3	0	0	0	**1.2**	0.73	0.33
TLx - 1992	2.03	3.04	2.33	2.76		**2.54**	0.23	
TLx - 1993	2.58	3.25	2.37	2.80		**2.75**	0.19	
TLx - 1994	2.16	3.14	2.54	2.78		**2.65**	0.21	
Avs. of TLc, TLs, TLp, TLn, TLI, p-values	**2.26**	**3.15**	**2.41**	**2.78**		**2.65**	0.11	**0.26**
Time Trend in TLI = 0.06 ± 0.09 levels/yr.								

*Non-significant changes are bracketed.

The table above summarises the results of monitoring the trophic state variables in Lake Brunner. The TLI time trend of 0.06 ± 0.09 indicates a possibility of no change. The average of the PAC and CTS p-values is 0.26 and is a weak indication of possible change. The assessment is that the trophic state of the lake may be changing and that it needs further monitoring. The TLI of 2.7 ± 0.1 units indicates that the lake is oligotrophic, with the relatively high value of TLs reflecting the beech forest staining of the lake water.

CHAPTER 25

25.0 LADY LAKE

Lady Lake is a highly coloured beech forest lake near Lake Brunner. It is small and shallow being about 1.5 km long and 22m deep. Lady Lake was monitored for just over two years from February 1992 to June 1994. There were 68 epilimnion samplings with only 46 and 45 Chla and TN values obtained respectively. There were 32 hypolimnion samplings with only 21 TN values obtained. No real trend is available with only two years of data.. An outline of this lake is shown in Fig. 25.0.

25.1 Physical Variables

25.1.1 Lake Depth

Lake depth remained between the 21.6 to 22.6m range with lowest levels in the autumn and spring (Fig. 25.1A).

25.1.2 Temperature

The epilimnion temperature range is quite large being from 20^o to 7^{o}C (Fig. 26.1C). The lake in 1993/94 was significantly warmer than in 1992/93 (Fig. 26.1D) with temperature increasing at the rate of 0.55^{o}C per year. The hypolimnion temperatures are quite variable (Fig. 25.1E) with the 1992 temperatures being lower than the others (Fig. 26.1F). The temperature rise in the hypolimnion during 1993 was from 9^o to 10.4^{o}C (Fig. 26.1F) which indicates fairly extensive downward mixing of thermocline waters.

25.1.3 Dissolved Oxygen

The average hypolimnetic DO concentrations dropped from 8 g m^{-3} in December to 0.0 mg m^{-3} in June (Fig. 25.1G), although absence of DO was recorded in March and April in 1992. The hypolimnion never went completely anoxic, however, since there was always NO_3 present together with low concentrations of DRP in these waters. It would seem that the rate of downward transport of DO was enough to prevent anoxia and the subsequent nutrient regeneration.

25.2 Trophic State Variables

25.2.1 Chlorophyll *a*

Chla has a definite pattern of higher concentrations present in the summer with lower concentrations in the winter (Fig. 25.2A). There was no significant trend (Fig. 25.2B) with time.

25.2.2 Secchi Depth

The SD annual pattern does not appear to be cyclical with high SD values in December followed by very low ones in January (Fig. 25.2C). This is largely due to the low SD values in January 1994 (Fig. 25.2D) associated with high Chla values at that time (Fig. 25.2B). There was no significant trend observed in SD.

25.2.3 Total Phosphorus

TP shows lowest concentrations in September and some relatively high ones in May (Fig. 25.2E) with the high May concentrations appearing in different years. These high concentrations are probably the result of upward mixing of deeper waters at that time of year. No trend in TP values is shown in either the epilimnion (Fig. 25.2F) or hypolimnion (Fig. 25.4A). The Pdiff data (Fig. 25.3A,B) is almost identical to the TP data.

25.2.4 Total Nitrogen

There is no real annual pattern in TN concentrations (Fig. (Fig.25.2H) but there is a significant ($p<0.01$) increase over the brief period that they were measured (February 1992 to September 1993). No meaning is attached to this trend in either the epilimnion (Fig. 25.2H) or hypolimnion (Fig. 25.4B). The TON annualised data (Fig. 25.3C) shows a very clear pattern of high values in the late summer. The TON time trend data (Fig. 25.3D) is more similar to the Chla data (Fig. 25.2B) than the TN data, indicating that TON values can relate to the phytoplankton in this lake.

25.3 Other Variables

25.3.1 Soluble Nutrients

Surface NO_3values show the normal pattern of being high in the spring, decreasing to low values in the summer (Fig. 25.4C). NO_3 concentrations do not go to zero in the hypolimnion (Fig. 25.4D) indicating the absence of anoxia.

Surface NH_4 concentrations are relatively low all year (Fig. 25.4E) while the NO_3 concentrations change considerably indicating that NO_3 is the main nitrogen nutrient utilised by phytoplankton.

The surface DRP values remain very low all year (Fig. 25.4G) indicating phosphorus limitation to growth. The hypolimnetic DRP values remain remarkably low (Fig. 25.4H) and thus provide a very low level of phosphorus resupply to the epilimnion.

25.3.2 Temperature/DO Profiles

The epilimnion usually extends to 4m depth and the hypolimnion starts at 15m depth. The T/DO profiles indicate that the hypolimnion is not well mixed with a gradation in temperature and DO concentration with depth and the near-zero DO values only occurring close to the bottom (Figs. 25.5A,B).

25.3.3 Turbidity, pH, Conductivity

Both the epilimnetic and hypolimnetic turbidities can vary considerably with quite high values occurring in the winter (Figs. 25.5C,D) when the Chla concentrations are low, indicating a high rainfall or resuspension effect.

The pH values are comparatively low being mostly less than 7.0 (Figs. 25.5E,F) and the EC values (Figs. 25.5G,H) are also relatively low.

25.4 HVOD Rates

The HVOD rates for the two different summers are shown in Table 25.2 and vary noticeably, but more data will have to be obtained to determine whether this is the normal pattern. The reoxygenation is comparatively high at an average value of 9.75 mg m^{-3} day on an average observed value (at 10^{o}C) of 46.3 mg m^{-3} day or 21% of the observed value. The temperature increase rates are more erratic than in most lakes (Fig. 25.6) indicating large scale downward mixing.

25.5 Phytoplankton Phenomena

One aggregated sample was analysed for phytoplankton species and biomass. The results are shown in Table 25.3.

25.6 Conclusions

It is not possible to determine trends of change in Lady Lake because the data record is too short.

Table 25.0

Lady Lake	Chla	SD	TP	TN	Avs. of TLx=TLI values	Std. Err.
TLx - 1993	2.34	3.91	2.98	3.21	3.11	0.32
TLx - 1994	2.26	3.91	3.21	3.36	3.19	0.34
Avs. of TLc, TLs, TLp, TLn, TLI.	2.30	3.91	3.09	3.29	3.15	0.22
Time Trend in TLI was not determined.						

A summary of the results of monitoring the trophic level variables is shown in the table above. The TLI of 3.2 ± 0.2 units indicates that the lake is a low range mesotrophic lake and it could almost be considered as on oligotrophic lake were it not for the high relative value of TLs which results from the beech forest staining of the water and also from the possible resuspension of bottom sediments because the lake is comparatively shallow for a stratified lake.

CHAPTER 26

26.0 LAKE TEKAPO

Lake Tekapo is a large, deep lake which is oligotrophic but which has a very shallow Secchi depth value because it has a high content of glacial flour. Lake Tekapo was only sampled for four months and was found to be comparatively difficult to sample, as it is deep and often rough. Continued sampling would have required a larger vessel and an extended depth oxygen probe. The available funding could not meet these requirements and the sampling of the lake was discontinued. The position of the sampling stations is shown in Fig. 26.0.

The data which was collected is shown in Table 26.1.

CHAPTER 27

27.0 LAKE HAYES

Lake Hayes was included in the LMP because it has high tourism value and a history of deteriorated water quality. The management of the catchment has improved and it is hoped that this will result in an improvement of the water quality of the lake. It is about 3 km long and 1.1km wide. The sampling of Lake Hayes provided 116 values for most epilimnion variables and 90 values for the hypolimnion variables. Fig. 27.0 shows an outline of the lake with the position of the sampling stations.

27.1 Physical Variables

27.1.1 Lake Height and Depth

The lake depth is the lake height plus 32.0m. The scale of the lake height plot gives a better idea of changes in depth (Fig. 27 1A,B). There is a weak pattern of lowest lake height occurring at the end of summer (Fig. 27.1A). Over the 4.5 years of monitoring the lake has shown a trend ($p<0.01$) of increasing depth by 6 cm per year (Fig. 27.1B).

27.1.2 Lake Temperature

The maximum epilimnion annualised temperature of the lake in summer is 18^{o}C and the isothermal lake in winter drops to 5^{o}C (Fig. 27.1C) There has been a surface water temperature increase of 0.22^{o}C per year ($p<0.01$) (Fig. 27.1D). The hypolimnion of the lake shows a general increase from 6.5^{o}C in early October to 8.8^{o}C in April (Fig. 27.1E). During late April and May there is little temperature increase. The long straight line segments in Fig. 27.1F occur when there is no hypolimnion in existence.

27.1.3 Dissolved Oxygen

Fig. 27.1G shows that the hypolimnetic DO concentration decreases rapidly after stratification commences in early October. The hypolimnion becomes anoxic by February and continues in that condition until May (Figs. 27.1G and 27.5B). The critical 3.0 g m^{-3} DO concentration is reached in December indicating that the January DO concentration must be used with care in DO depletion rate calculations; the DO values from February onward cannot be used.

27.2 Trophic State Variables

27.2.1 Chlorophyll *a*

Chla does not show any strong annual pattern (Fig. 27.2A), but does show a significant decline ($p<0.01$) of 1.8 mg m^{-3} per year, partly due to the high values experienced during 1992. Slightly higher levels show again in 1996. The PAC value is -23.9% yr^{-1} on an average Chla of 7.62 mg m^{-3}. The change in Chla yields a CTS value of -3.

27.2.2 Secchi Depth

Although the annualised average shows the maximum SD in July, the clearest waters are found in the autumn and spring (Fig. 27.2C). High Chla levels can be found in July (Fig. 27.1A) because of the nutrients mixed up from the bottom waters in May. SD shows some stability over the years of monitoring with an insignificant slope to the trend lines. SD has a CTS value of 0.

27.2.3 Total Phosphorus

TP concentrations in the surface waters show considerable variation from concentrations of 10-20 mg P m^{-3} in the summer to 50-70 mg P m^{-3} in the winter (Fig. 27.2E). The concentrations are particularly high in May when the hypolimnetic waters mix upwards. The concentrations in June may be even higher but the lake wasn't sampled at that time. The deseasonalised TP values show a significant decline ($p<0.01$) during the years of monitoring of 2.2 mg P m-3 yr^{-1} which gives a PAC value of -6.9% per year on the average TP concentration of 32.2 mg P m^{-3}. The change in TP concentrations gives a CTS value of -3 for the monitored period.

Pdiff shows a different pattern (Fig. 27.3A) from TP because the effect of the large and variable DRP values is not included in Pdiff, as it is largely the organic phosphorus in the lake. Fig. 27.3B shows a decline in Pdiff as does TP but the Pdiff decline is not statistically significant.

27.2.4 Total Nitrogen

The TN concentrations vary from the lowest values in autumn to the highest values in early winter (Fig. 27.2G) due to upward mixing of the enriched hypolimnion waters. The TN values show a significant decline ($p<0.01$) of 14.4 mg P m^{-3} yr^{-1} to give a PAC value of -3.6% per year on an average concentration of 399 mg N m^{-3}. This decline gives a CTS value of -3 for TN.

Since the concentrations of NH_4 and NO_3 are large, the TON annualised pattern (Fig. 27.3C) is quite different from that of TN, showing the TON to be at its lowest value in mid-winter. There is a significant ($p<0.02.$) decrease in TON with time (Fig. 27.3D) in agreement with the decrease in Chla (Fig. 27.2B).

27.3 Other Variables

Fig. 27.4A shows the large increase in hypolimnetic TP each summer from lows below 50 to highs greater than 250 mg P m^{-3}. Hypolimnetic TN values follow a similar but more erratic pattern with some very high concentrations observed before the end of stratification (Fig. 27.4B). Surface NO_3 values show an increase each year from low values in the summer to high values in the following spring when concentrations again drop rapidly (Fig. 27.4C). Hypolimnetic NO_3 concentrations rise rapidly from October to December each year and then drop as the DO concentrations drop and denitrification sets in (Fig. 27.4D). The reason for the decline of hypolimnetic NO_3 values ($p<0.01$) could indicate that low DO conditions occurred earlier each stratified period which would agree with the non-significant increase in the HVOD rates (Fig. 27.6). Surface NH_4 values are high during the winter and very low during the summer (Fig. 27.4E). The commencement of the hypolimnetic NH_4 increase (Fig. 27.4F) is variable, sometimes starting with stratification in October and sometimes delayed until December (1992, 1993) when DO concentrations are low.

Surface DRP values are similar to those for NH_4 in being very low in the summer and high in winter (Fig. 27.4G). In fact, NO_3, NH_4 and DRP values all drop to very low levels at about the same time in early summer and remain low all summer, indicating that both nitrogen and phosphorus are limiting to algal growth.

Fig. 27.5A shows that the surface waters reached 120% DO saturation in December 1995, indicating strong algal growth. Fig. 27.5B shows that in April 1996 the anoxia extended up into the thermocline.

Surface water turbidity and conductivity showed significant declines ($p<0.01$) (Figs. 27.5C,G) as did hypolimnetic conductivity with a very marked decline (Fig. 27.5H). The reasons for these trends are not known. Figs. 27.5E and F showed no time trend for pH.

27.4 Dissolved Oxygen Depletion

Fig. 27.6 shows the hypolimnetic DO and temperature data for the four summers from September 1992 to January 1996. Eight values for both DO and temperature were acceptable and gave significant trends ($p<0.01$). The values for January of each year were below 3 g m^{-3} DO and were inspected carefully to see that they did not distort the slope available from the DO concentrations above 3 g m^{-3}. The rates derived from Fig. 27.6 are shown in Table 27.2. The observed rates showed no significant trend with time. The reoxygenation corrections were variable because temperature increase slopes shown in Fig. 27.6 were variable. The final adjusted rates show a non-significant upward trend (Fig. 27.7).

The HVOD rates, while not statistically significant when using a p-value criterion for HVOD rates of 0.20, do indicate that the trend is to increase with time. This does not agree with the signal of decreasing trophic state from the Chla, TP and TN trends. However, the most reliable HVOD rates might be the temperature corrected observed rates which indicated very little change with time.

27.5 Phytoplankton Phenomena

Two aggregated samples from Lake Hayes were analysed and the results are shown in Table 27.3.

27.6 Conclusions

A summary of the results of monitoring the trophic state variables in Lake Hayes is shown in the table below.

Table 27.0

Lake Hayes	Chla	SD	TP	TN	HVOD	Avs. of PAC, CTS values and of TLx=TLI values	Std. Err.	p-values
PAC (%/yr)	-23.9	(-0.7)	-6.9	-3.6	(+1.6)	**-6.9**	4.4	0.07
CTS (units/yr)	-3	0	-3	-3	0	**-1.8**	0.73	0.19
TLx - 1992	4.86	3.86	4.67	4.32		**4.43**	0.22	
TLx - 1993	4.10	3.68	4.66	4.29		**4.18**	0.20	
TLx - 1994	4.12	3.79	4.51	4.17		**4.15**	0.15	
TLx - 1995	4.27	3.83	4.47	4.14		**4.18**	0.14	
Avs. of TLc, TLs, TLp, TLn, TLI, p-values	**4.34**	**3.79**	**4.58**	**4.23**		**4.23**	0.34	**0.13**
Time Trend in TLI = -0.08 ± 0.05 levels/yr. This trend is confirmed								

*Non-significant changes are bracketed.

The average of the PAC and CTS p-values is 0.13 and indicates that Lake Hayes has probably improved as is indicated by the TLI time trend. The TLI of 4.2 ± 0.3 means that the lake is eutrophic. The TLs for Lake Hayes is comparatively low because Lake Hayes is a stratified lake with little resuspended material in its water column. Most of the eutrophic lakes in New Zealand are shallow lakes and it is data from them which determines the relationship between Chla and SD in eutrophic lakes, with a fairly high level of resuspended material in the water column of these shallow lakes. This resuspended material is largely absent from deeper eutrophic lakes, hence their lower TLs values. Since both the dissolved nitrogen and phosphorus nutrients are down to growth limiting levels in the summer, the clear downward trend of TP and TN with time is worth watching with continued monitoring. If these trends continue downward, the trend toward oligotrophic conditions could be considered more probable.

CHAPTER 28

28.0 DRAFT RECOMMENDATIONS FOR COST-EFFECTIVE MONITORING STRATEGIES

28.1 Baseline Monitoring Programs

The following section describes the nature of a monitoring programs that should be put in place on lakes where good data has not been consistently collected in the past. As far as possible, each Regional Council should obtain as minimum baseline data, two years of monthly samples from each significant lake in its region. This reference information would become increasingly important with time in the sustainable management of lakes, in determining for example, in the year 2025 whether a lake had changed in from what it was in year 2000.

28.1.1 Stratified Lakes

Since the HVOD data were seen to be less reliable than the Chla, SD and TN data at predicting change in a lake, only one temperature/DO profiling station should be chosen, not two stations as in the LMP. The selected station should always be at the deepest point of the lake if possible. A second 'epilimnion-only' sampling station should be located midway between the deep station and the boat launching ramp, if it is appropriate. The idea is to obtain a set of samples from water closer to the shoreline than that obtained from the deep station. Epilimnion samples should be taken from both of these stations by using four van Doorn sampling casts between the surface and bottom of the epilimnion or by using an integrating tube sampler down to the bottom of the epilimnion, during the stratified period. The K values and the Z_{samp} , described in Volume 2, Section 1.2 need not be used to set the upper layer sampling thickness. This layer would be the epilimnion layer as determined from the T/DO depth profile taken at a station. It would be divided by 4; and then sampled at depths of 0.1m, ¼, ½, and ¾ of the epilimnion thickness. A single hypolimnion sample should be taken from the middle of the hypolimnion when it contains oxygen at all depths. If it has an anoxic layer, two hypolimnion samples should be taken, one each from the center of the oxic and anoxic layers. The determinands for analysis would be the same as in Volume 2, Table 1.1 except that turbidity and suspended solids should be omitted. Suspended solids are not necessary for stratified lakes. The sampling should be monthly and the program should continue for two years, by which time the information on the basic limnology of the lake would be available and baseline values for the variables listed in Table 1.2 would have been obtained.

28.1.2 Unstratified Lakes

The recommended baseline monitoring strategy for isothermal lakes is the same as that described in Volume 2, Sections 1.4 to 1.8 with one important addition to the present LMP methodology on shallow lakes. The LMP was shown that the nature of a shallow lake is very dependent on the biomass of macrophyte species and their distribution in the lake. Thus, a macrophyte survey according to the method described by Clayton (1983) should be carried out annually.

28.2 Minimal Monitoring Programs

28.2.1 Stratified Lakes

Since keeping costs as low as possible and optimising cost/benefit returns is a serious concern for Regional Councils, the design of minimal, low-cost monitoring programs is important. This type of program could be implemented on lakes where there is good background data available or would be suitable for continued sampling of any of the LMP lakes which have been sampled for two years or more. The program would be similar to that described above (28.1.1) with some selected omissions. No more samples should be analysed for pH, EC or soluble nutrients and no samples would be taken from hypolimnion waters. This minimal program should concentrate on sampling Chla, SD, TN, TP in the epilimnion and DO in the hypolimnion. The assumption would be made in assessing the data that the patterns of concentration change in the epilimnetic and hypolimnetic soluble nutrients would continue to be similar to those shown in the two years of baseline sampling. Algal samples should be collected for analysis if a good quantitative method for assessing phytoplankton community change can be developed (see Section 28.4). Each year the data for each determinand from the past year would be added to the record to enable new plots of both the annualised pattern and time trends for the four basis trophic state variables to be produced. They should be plotted on a large scale and compared carefully with the plots from the previous year. If a series of significant changes in the time trend plots are observed, then the minimal lake monitoring program would no longer be adequate and a new diagnostic investigation would have to be implemented. When the cause of the lake deterioration is identified, management procedures to rectify the situation should be put in place. However, since obtaining a sample usually costs more than analysing it for nutrient content, the costs of the nutrient analyses should be carefully assessed against benefit before deciding to eliminate non-essential analyses. When changes occur, the dissolved nutrient values often provide clues as to the cause of the change.

28.2.2 Unstratified Lakes

The minimal monitoring program on unstratified lakes would be very similar to that carried out on stratified lakes except that no attempt would be made to calculate HVOD rates. The minimal program should only be carried out on isothermal lakes that had a two year data record on all the variables measured in the LMP, with turbidity omitted and with the addition of macrophyte surveys. As these surveys are time-consuming, their frequency would depend on the degree of change being observed in a lake; significant change in Secchi depth would require more frequent macrophyte surveys. The time trend data would be analysed carefully for change, in the same manner as that collected from stratified lakes.

In all cases where the monitoring has proceeded for more than three years, the time trend plots would have to be examined with care; to ascertain that linear plots were only being attempted where appropriate. If breakpoints are evident in the data as in Figs. 6.2 and 6.4, Volume 3, then the periods for suitable linear approximation to the data must be carefully chosen.

28.3 Frequency of Sampling

28.3.1 Within-Year Sampling Frequency

The monthly sampling period appears to have worked well with most stratified lakes. The change between the stable, summer, stratified state to the unstable unstratified winter state and back, takes a month or more in each case and is easily observed with monthly sampling. Both the stratified and unstratified states endure long enough for several monthly samples to be taken of them in most lakes. For some very stable lakes such as Rotoiti SI, monthly samples may not be necessary during the stable periods and some monthly samples could be omitted. However, for Lake Dudding, weekly sampling would have been required for a period just before and after stratification set up, if one wanted precise information on this lake because of its rapid rate of deoxygenation.

Since stratified lakes show patterns of large concentration change with change of season such as Chla in Lakes Okataina or Tarawera Volume 3, (Figs. 16.2A, 18.2A) or TP in Lake Hayes Volume 3 (Fig. 27.1E) it is important that monthly samples be taken when the seasons are changing. Weather can delay or advance seasonal cycles and a May sampling one year could catch a peak while in another year it could sample a trough. Nevertheless, it is possible to reduce the number of samplings per year to be less than twelve if the annualised patterns of change are carefully studied and reduced sampling frequencies are allocated to stable periods of little or no concentration change in the key variables. However, decisions on reductions to monthly sampling can only be made after monthly sampling data have been collected on a lake for a number of years.

Shallow lakes are not as seasonal as deep lakes, as they are more strongly disturbed by wind or rain events and the appearance or disappearance of macrophyte beds. Since the frequency of major weather perturbations is impossible to predict, it is difficult to nominate the optimum frequency for sampling shallow lakes. Changes in Hamilton Lake (Rotoroa) have been satisfactorily followed for five years with only eight samplings per year after the initial period of monthly sampling for two years. In fact, the sampling frequency per year for a shallow lake can be set by considering the importance of detecting a trend of change in the lake. The speed of detecting change in a shallow lake will be strongly related to the frequency of sampling.

28.3.2 Between-Year Sampling Frequency

If, after obtaining the minimum baseline data on lakes in a region, a Regional Council is faced with inadequate funds to sample all the lakes in its region, how then should it structure its sampling program?

All the lakes in a region should first be ranked in importance to the region. The assignment of monitoring funds should then be on the basis that the most important lakes are sampled each year; the next most important group of lakes should be sampled every second year and the third category, every third year. This is probably a better routine for the second group of lakes than their being sampled for two years consecutively then being unsampled for two years. Similarly for the third group of lakes the routine suggested above is better than one of sampling this group for two years followed by a non-sampling period of four years. The length of the period of non-sampling should be kept to a minimum, irrespective of the importance of a lake.

28.4 Possible use of phytoplankton data

Phytoplankton species biomass data could provide valuable information on lake trophic level change, independent of that provided by the other trophic state variables. However, the results of the LMP annual aggregated phytoplankton sample analysis has shown that this minimal level of analysis was inadequate to show changes in the phytoplankton population with time. A start to finding a method for using phytoplankton data to enable it to be a sensitive measure of change, would be to investigate the data obtained from samples collected and analysed 8 times a year from Lake Rotoroa for six years. A further investigation into the species associated with both oligotrophic and eutrophic lakes would also be needed. This phytoplankton data would be examined to see if a method could be found whereby this data could demonstrate decreasing eutrophy in the lake as the chemistry data has done. This information would determine whether phytoplankton could be used as a sensitive trophic level indicator.

NOTE

It must be acknowledged that a certain amount of intuition, based on a good knowledge of the LMP results, has been used in making the recommendations here.

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