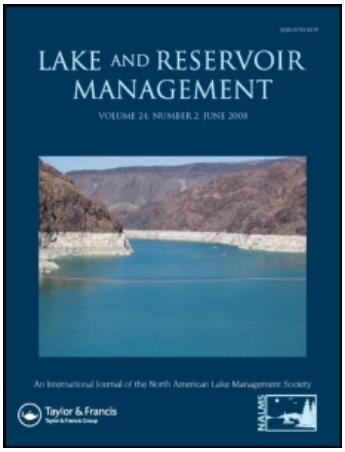


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# A Monitoring and Classification System for New Zealand Lakes and Reservoirs

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# A Monitoring and Classification System for New Zealand Lakes and Reservoirs

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## ABSTRACT

Burns, N. M., J. C. Rutherford and J. S. Clayton. 1999. A monitoring and classification system for New Zealand lakes and reservoirs. Lake and Reserv. Manage. 15(4):255-271.

Five variables gave strong indications of change in the trophic state of New Zealand lakes, namely; concentrations of chlorophyll *a*, total phosphorus and total nitrogen, as well as Secchi depth and dissolved oxygen depletion rate. The New Zealand Lake Monitoring Program, investigated 17 lakes for 3 to 4 years to develop a method for detection of small changes in these five variables and to develop a cost-effective monitoring system for lakes. Two different methods were developed which enabled trends observed separately for variables to be combined into an indicator of change (PAC, Percent Annual Change) and an index of trophic state (TLI, Trophic Level Index). The PAC is a relative indicator that gives the average percent annual change of the trophic state variables, and is an indicator of the magnitude of the change observed. It is calculated from the 5 variables listed above. The TLI is a numerical indicator of lake trophic level, which typically varies from 2 (oligotrophic) to 7 (supertrophic). The TLI can be examined for time trends that generally reflect the changes detected by the PAC relative indicator. These two indicators, when used together, give a good estimate of the probability and magnitude of trophic level change in a lake as well as the trophic level of the lake. Results for all the monitored lakes are given. The PAC and TLI indicators also gave useful results when used to study reservoir monitoring data.

Key Words: lake monitoring, trophic level assessment, trophic level index, indicators of change, deseasonalising procedure.

Lake monitoring can be undertaken to determine the state of a lake, or as is more common, to determine the change in the state of a lake over time. The objectives of the New Zealand Lakes Water Quality Monitoring Programme (NZLMP) were to provide a good database on the trophic condition, in the 1990s of some of New Zealand's better known lakes and use this database to develop a sensitive, cost-effective Lakes Monitoring Protocol for detection of small degrees of change in the trophic state of lakes.

The NZLMP was started in February 1992 and sampling ceased in June 1996. Twenty-three New Zealand lakes were sampled with 17 of the lakes monitored for periods from 3 to 4 years. A broad spectrum of lake types were sampled from across the country to enable a widely applicable monitoring methodology to be developed. However, no large, deep lakes were included in the programme because the funding for the NZLMP did not permit the expense of monitoring this type of lake. To assist in the formulation of a Lakes Trophic Index that is suitable for a wide range of New Zealand lake types, data from Lake Taupo, a large, 622 km$^2$ lake, was made available by Environment Waikato, Hamilton, New Zealand. The lakes that were monitored are shown in Fig. 1.

[1] Noel Burns did most of the work on this study while he was an employee of NIWA in Hamilton.

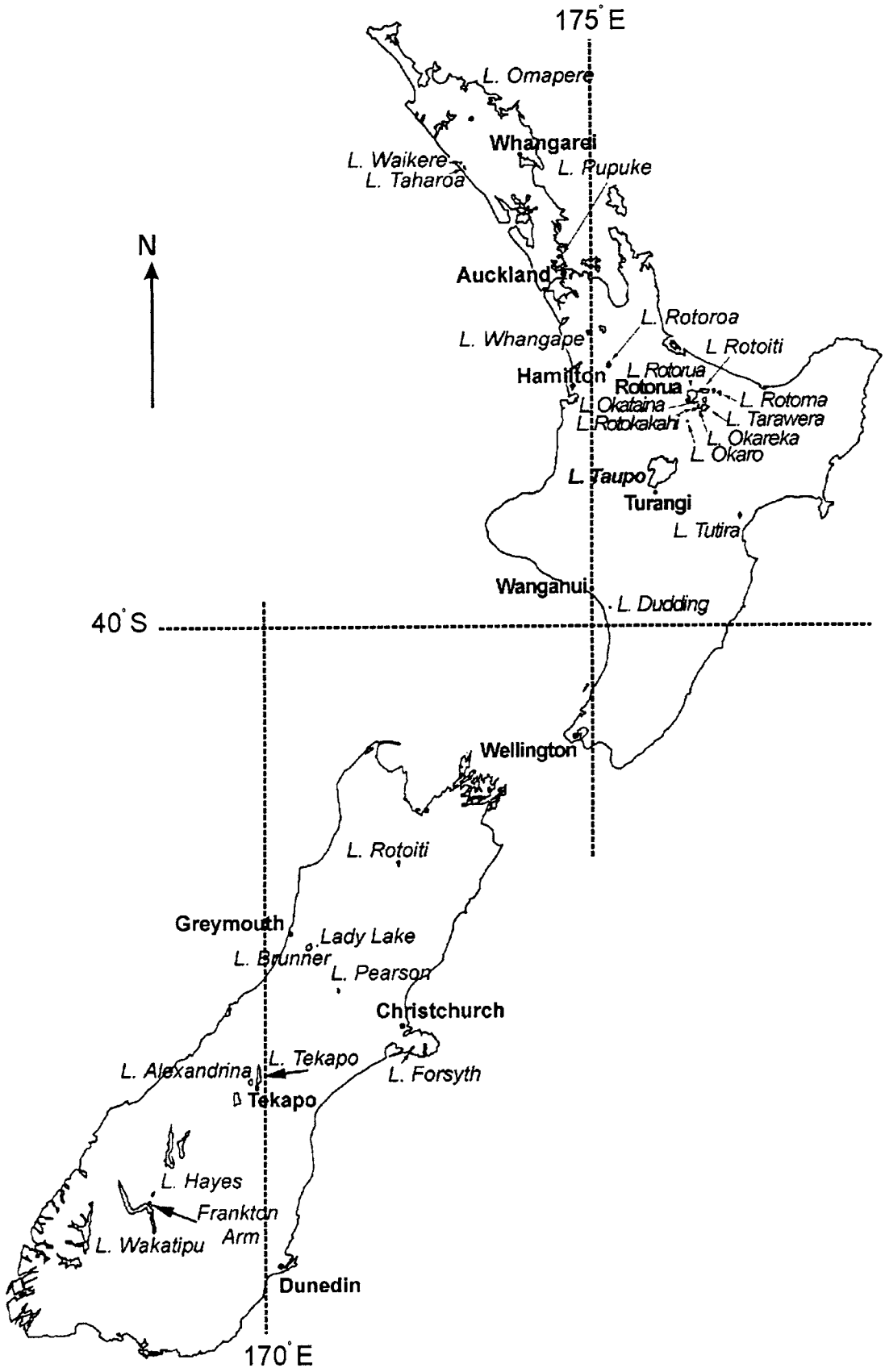



**Figure 1.–Map of New Zealand showing the lakes monitored as part of the New Zealand Lake Monitoring Program. Lake Taupo was monitored separately.**

# Concepts Determining the Design of the NZLMP

The concept of 'the trophic state of a lake' is complex and not easily defined in precise terms, yet almost all limnologists would have their own clear personal idea of what constitutes 'trophic condition'. The commonly accepted variables that define lake trophic condition are; chlorophyll *a* (Chla), Secchi depth (SD), total phosphorus (TP), total nitrogen (TN), hypolimnetic volumetric oxygen depletion rate (HVOD), and phytoplankton species and biomass (Vant 1987). These parameters were measured in the isothermal or epilimnion waters of the stratified NZLMP lakes except for HVOD, which was calculated from hypolimnetic dissolved oxygen profiles. They are referred to below as the key variables.

The existence of hypolimnetic anoxia has been used as an indicator of eutrophic conditions (see White 1977, for example) but it is not a reliable indicator of poor lake condition. Lake Rotokakahi, for example, undergoes almost 2 months of hypolimnetic anoxia each summer but has an annual average Chla concentration of only 2.3 $mg \cdot m^{-3}$ and could almost be classified as an oligotrophic lake. (Oligotrophic lakes have annual average Chla values of $< 2.0$ $mg \cdot m^{-3}$.) Nevertheless, changes in HVOD rates with time can be informative about change in trophic condition and this variable is used in assessment of change of trophic level.

The reason for determining whether a lake has undergone a small degree of deterioration is to enable the start of remedial work before the lake has undergone extensive degradation. Large scale change in the trophic condition of a lake is easy to detect because obvious, consistent changes usually occur in all six of the key variables, i.e. the observed changes all indicate either degradation or improvement. However, when there is no real change in trophic level of a lake, these variables can vary independently from each other. For example, if phytoplankton growth is limited by phosphorus availability, TN can increase without an increase in phytoplankton abundance. Phytoplankton species can change from those with a relatively low Chla content to others containing a higher Chla concentration and thus increase the Chla content of the lake, when little else has changed. Floods can bring much organic and/or inorganic matter from the catchment into a lake; the organic matter can affect the oxygen depletion rate and the inorganic matter will alter the SD, but little else in the lake may have changed.

However, a small but definite change in trophic state will cause consistent changes to occur in all of the key parameters although these changes may not all be observable because of short-term variability and the associated difficulty in detecting a small degree of change in a parameter. To develop a sensitive method of detecting change of trophic state, all six key variables were monitored and methods sought for combining the information from them into indices of change so as to improve the possibility of detection of change in trophic state. Thus, means were sought to express the changes observed in the key variables in the same units so that the results of observations of change in the different variables could be added together and averaged.

In addition, efforts were made to find an appropriate way to express the actual values of the key variables in Trophic Level units that are common to all the variables, so that they could be combined into a Trophic Level Index (TLI) value for each lake. A convenient index would be one structured to categorise the trophic state of lakes in a systematic numerical manner with each integer value of the classification scheme designating a different class of lake. If changes are observed in the trophic variables in a lake with time, the calculated TLI for that lake should be found to change with time in a manner that reflects the observed changes.

The sampling carried out in the NZLMP was not purely for monitoring purposes, which would have required sampling and analyses only for the key variables, but also to provide basic limnological background data on each lake. Thus, samples were also analysed for dissolved nutrients, pH, and conductivity. This descriptive aspect of the monitoring programme could be dropped after a few years of gathering background information to save money, with continued collection of data on the key variables only.

# Methods

## *Sampling*

Two sampling stations were chosen on each lake, one at the deepest point and the other at another deep part of the lake at some distance from the first station. On arrival at a sampling station, a Secchi depth measurement was taken and the temperature/dissolved oxygen profiles were obtained and plotted. Depths for the bottom of the epilimnion and top of the hypolimnion were determined for the purpose of selecting sampling depths. Isothermal, well-mixed waters exist in shallow lakes all year and in almost all New Zealand lakes during the winter, as very few lakes undergo winter

stratification. Deeper lakes stratify for periods of four to seven months over summer. The lakes were sampled on a monthly basis.

### Isothermal lakes

If a lake was not stratified, the sampling protocol was straightforward. Samples were collected at 1/4 and 3/4 of the depth at the sampling station using a van Dorn bottle. At the upper sampling point, three 2.2 litre samples were collected and mixed, and then subsampled into a 1 litre bottle for nutrient analysis, a 100 mL algal sample, and a 5 litre bottle (for filtering on shore for subsequent Chla analysis). A single van Dorn sample was collected at the lower sampling point from which a 1 litre bottle was filled: this was kept for nutrient analysis. This lower sampling point was changed if the bottom waters were anoxic and the lower sample was then taken in the mid-point of the anoxic layer. The operational definition for anoxia was a reading less than 0.3 g $m^{-3}$ dissolved oxygen (DO) to account for possible probe errors in such low saturation waters. This occurrence was infrequent and only happened if there was a lengthy calm period that did not mix the isothermal waters to the bottom of the lake. Because shallow, unstratified lakes are often very perturbed by weather events, causing resuspension of bottom materials by strong winds, total and inorganic suspended materials were measured in shallow lakes to gauge the magnitude of this effect at the time of sampling.

### Stratified lakes

Epilimnion sampling. Because a relatively thin turbid layer of detritus is often present near the thermocline, only the top 80% of the upper mixed layer depth was sampled. Four 2.2 litre samples were collected using a van Dorn bottle, one sample just below the surface, one at 80% of epilimnion depth and two others equally spaced between these depths. The samples were then pooled in a large container. They were subsequently subsampled into 1 litre, 100 mL and 5 litre bottles. The Chla samples were filtered in duplicate on shore from the 5 litre sample.

Hypolimnion sampling. Samples were collected (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. These were mixed and a single 1 litre subsample taken for nutrient analysis. However, if there was a deoxygenated zone (i.e., less than 0.3 g $m^{-3}$ DO) then the lower sample was collected in the middle of the anoxic zone, and the two samples were not mixed; a 1 litre subsample was taken for nutrient analysis from each separate sample. The anoxic waters were sampled separately from the oxygenated waters to determine whether high concentrations of nutrients were present in these waters.

## *Determinants*

The samples were analysed for TP, TN, dissolved nutrients, pH, conductivity and turbidity. Samples from the shallow, unstratified lakes were also analysed for total suspended materials (TSS), and inorganic suspended materials (ISS). These variables provided background information on the degree of sediment resuspension at the time of sampling. The analytical methods used are listed in Table 1. Lake levels were also measured each month.

The HVOD rates were determined using the methods of Burns (1995). No HVOD rates were calculated for periods when hypolimnetic DO concentrations of less than 2 g $m^{-3}$ were observed. A single HVOD rate and average hypolimnetic temperature were calculated for each lake each year. A standard hypolimnion temperature was chosen for each lake for the 3 or 4 years of monitoring and the HVOD rate for a lake for a season was adjusted to be the rate expected at the standard hypolimnion temperature. This adjustment for small average temperature differences resulted in an improvement in the consistency of the HVOD results for each lake.

Algal samples were subsampled from the epilimnion samples collected monthly. All the algal samples collected during a year from each lake were mixed into a single annual sample that was analysed for phytoplankton species and biomass. Thus, only one algal sample was analysed per lake per year to diminish the expense of analysing monthly samples for up to 23 lakes. Collection of algal samples commenced in December 1992.

## *Trend Detection*

The prime objective of the data analysis was to determine whether or not a significant change had occurred in any parameter with time. The seasonal changes in Chla, SD, and nutrient concentrations in a stratified lake are usually large and obvious and these changes can often mask small changes in trophic level. Temperature, Chla, SD, TP and TN, were deseasonalised prior to trend detection. With only one aggregated phytoplankton sample per year analysed, it was not possible to find any change in the phytoplankton data with time. This was even the case with Lake Omapere, which showed a large decrease in trophic level with time. Thus, the key variables in this investigation became Chla, SD, TP, and TN for unstratified lakes, and these four variables plus HVOD rates for stratified lakes.

**Table 1.–Analytical Methods used in the New Zealand lake monitoring program.**

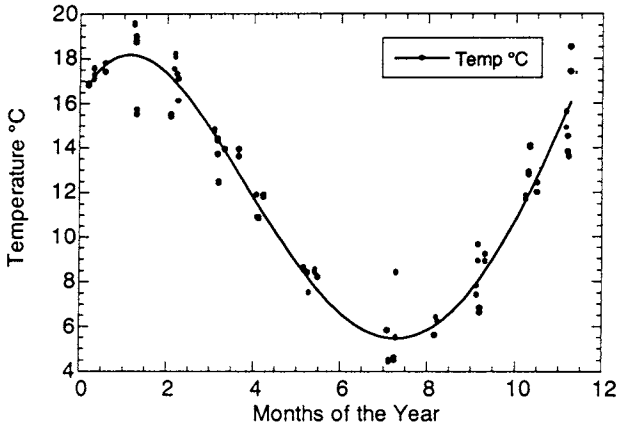
| Determinant | Method | Reference |
|---|---|---|
| Dissolved oxygen | Probe YSI 5739 with stirrer<br>Meter YSI No. 58 | |
| pH | Meter, Radiometer 26 | 2 |
| Conductivity | Meter, Radiometer CDM83 | 3 |
| Turbidity | Meter, Hach 2100A | 3 |
| Nitrate | Automated hydrazine sulphate reduction | 4 |
| Dissolved reactive P | Automated ascorbic acid reduction | 6 |
| TP | Persulphate degestion, then manual ascorbic acid reduction | 2 |
| Ammonium | Automated phenol-hypochlorite | 7 |
| TN | Alkaline persulphate digestion, cadmium column reduction, nitrite finish | 1 |
| Suspended Solids | Loss of weight when combusted at 500°C | |
| Chlorophyll *a* | Acetone extraction, absorbence measurement | 5 |

References:
(1) Koroleff, 1983
(2) Smith et al., 1982
(3) Manufacturer's instructions
(4) Downes, 1978a
(5) Biggs et al. 1983
(6) Downes, 1978b
(7) Technicon, 1978

When there are three or more years of data available for a lake, it is possible to carry out a valid annualising procedure. Temperature provides a good test of the trend detection procedure used and is reported on here because the change of temperature of a lake during the year is relatively large and similar from year to year. Fig. 2A. shows the epilimnetic temperatures which were observed in Lake Hayes during the 4 years of monitoring, plotted only as a function of the time of year of collection with no regard for the year of collection. This process is called annualising the data. A polynomial curve was fitted to the annualised data as shown in Fig. 2A. The residual, deseasonalised value for any particular day is the observed value less the day/month value calculated from the polynomial for its day of observation. A polynomial formulation of the seasonal pattern was chosen rather than a sinusoidal one because, while change in temperature with time is sinusoidal, the patterns of change in Chla, SD, TP, and TN with time are frequently irregular.

The observed and residual data are plotted against time as shown in Fig. 2B and straight line plots are fitted to the residuals using ordinary least square (OLS) regression. A p-value is then calculated for the slopes of the lines fitted to the observed and residual data. A low p-value indicates 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. A program called Lakewatch (Knowlysis 1998) was used for the calculations. This program permitted selection of a polynomial of any order up to the twentieth, for fitting a curve to the deseasonalised data. The program then automatically calculated the residuals and plotted them and the observed data as a function of their true date of collection. It then fitted an OLS regression line to both sets of data and calculated the p-values of the linear fits. The procedure followed was to select the data for analysis using the program, Lakewatch, which would then annualise the data, calculate the third order polynomial to fit the deseasonalised data, calculate the residuals, fit regression lines to the observed data and residuals and calculate p-values of the regression lines. The order of the polynomial fit to the deseasonalised data was then increased by one, noting the p-value resulting from the new calculations. This procedure was continued until the order of the polynomial that gave the lowest resulting p-value to the linear regression fit to the residual data was found. This was usually a fourth to eighth order polynomial. Use of higher order polynomials did not result in lower p-values for the linear regression on the residuals. This procedure allowed the data to reveal the maximum amount of seasonality that could be removed from it.

Because the units along the x-axis of Fig. 2B 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 0.217 indicating that the



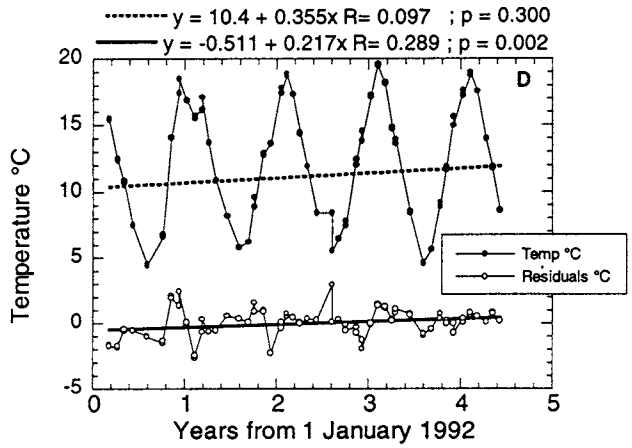




**Figure 2A.–Observed average epilimnion and isothermal temperatures for Lake Hayes from March 1992 to June 1996 with a fifth order polynomial curve fitted to the data.**

**Figure 2B.–Least square linear fits to observed temperatures and temperature residuals for Lake Hayes after subtraction of annualised seasonal values.**

temperature of Lake Hayes increased by 0.217°C per year. Residuals have been calculated and straight lines plotted for both residuals and observed data for temperature, and for the four variables that are the most informative about trophic state; namely, Chla, SD, TP, and TN.

It should be noted that p-values decrease as the number of samples increases. Thus the number of samples may determine whether or not a trend is determined to be significant. In this study, the number of epilimnion and isothermal samples from each lake over 3 or 4 years was between 100 and 200. The significance level for establishing that a trend has been detected with this number of samples was set at 5% ($p \leq 0.05$) for this study for Chla, SD, TP and TN. HVOD rates were also calculated for stratified lakes and these rates were plotted as a function of the year when they were obtained. A linear regression line was fitted to these values and a p-value calculated for the line. The significance level for a HVOD time trend was set at 20% (p-value < 0.20) because four years of data on a lake would yield only four HVOD rates. This relaxation of the significance level was done in recognition of the fact that p-values attained by tests such as used here depend on the number of samples collected as well as on the actual trend and its associated variability (see p. 168, Sokal and Rohlf 1981).

The annualising and trend analysis techniques used on the temperature data were used on Chla, SD, TP and TN data. This technique has the advantage of enabling trend analysis on data collected irregularly over the year. The results from these analyses were used in two different ways to quantify change in trophic state and are described in the following sections.

## *Percent Annual Change (PAC) values*

The percent annual change (PAC) value for the key variables was calculated by estimating the slope of a time trend in the deseasonalised data using OLS regression, and dividing this slope by the average value of the variable during the period of its observation. This is illustrated from the result in Fig. 3, showing the annual change in TP in Lake Hayes was –2.23 mg $P \cdot m^{-3} \cdot yr^{-1}$ with a p-value = 0.003. When this is divided by the average concentration for the period of 32.2 mg $P \cdot m^{-3}$, a PAC value of –6.9 % $yr^{-1}$ is obtained. Only PAC values calculated from significant trend lines are considered indicative of change in a lake. The PAC values for the different variables are expressed in the same units (% change per year) and thus can be

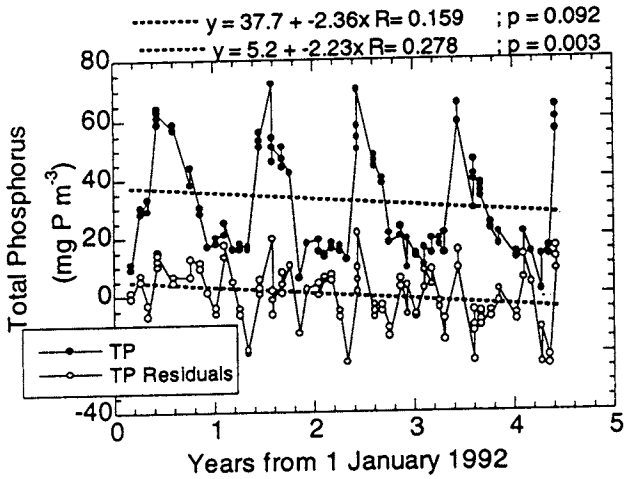



**Figure 3–Plots and linear least square fits of observed total phosphorus (TP) data and residual TP data after subtraction of annualised seasonal TP values. The residual TP values show a significant change of –2.23 mg $P\ m^{-3} \cdot yr^{-1}$.**

added together. The PAC values calculated from non-significant slopes are replaced by a value of 0.0. The PAC values from a lake are added together and averaged and a p-value obtained for this average. Changes indicating increased eutrophication are assigned positive values and changes indicating decreased eutrophication are given negative values.

The decision on whether a lake has changed over time is made by examining the p-value of the PAC averages. The assessment is made as to the probability of change having occurred by using the ranges of these p-values as shown in the table below. This scale of probabilities was devised using professional judgement when considering the results from the data of the 17 monitored lakes.

| p-value range of PAC averages | Interpretation |
|---|---|
| <0.1 | Definite Change |
| 0.1 - 0.2 | Probable Change |
| 0.2 - 0.3 | Possible Change |
| >0.3 | No Change |

## *A Trophic Level Index (TLI) for NZ Lakes*

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). Carlson (1977) and Chapra and Dobson (1981) have both proposed trophic state index schemes, shown in outline in Table 2 (with some of Vant's values from Davies-Colley et al. 1993), but neither of these schemes seemed appropriate to NZ lake conditions. Carlson's scheme is based on SD, with the SD of each new level being half that of the previous level, and results in large increases in the Chla concentrations in the higher trophic 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. Further, as many New Zealand lakes show aspects of nitrogen limitation to growth (White et al. 1985), TN becomes an essential variable in a trophic level index scheme for New Zealand lakes and neither Carlson (1977) or Chapra and Dobson (1981) included TN in their classification schemes.

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 and which includes TN. Since trophic condition is based largely on the biological condition of a lake, Chla, a biological variable was chosen as the primary variable defining the trophic condition of a lake. The annual average values for each lake for each year are used for calculating equivalent trophic level values (TLx) for Chla (TLc), SD (TLs), TP (TLp), and TN (TLn) where TLc is the TLI value determined only from Chla values.

The TLI scheme is based on Vant's values and TLc values 3, 4 and 6 were initially assigned to Chla concentrations of 2, 5 and 30 mg $m^{-3}$. A straight line plot was fitted to these values by using an OLS regression as shown in Fig. 4 and the equation,

$$TLc = 2.22 + 2.54\ log(Chla) \quad (1)$$

was obtained. The equation was a good fit to the points except that a TLc value of 6.0 was found to correspond

**Table 2.–Values of Chlorophyll *a* defining the mesotrophic state of lakes and their corresponding trophic state values as proposed by different authors.**

| Vant (1987) | Carlson (1977) | | Chapra et al. (1981) | | Burns et al. (this publ.) | |
|---|---|---|---|---|---|---|
| Chla ($mg \cdot m^{-3}$) | Chla ($mg \cdot m^{-3}$) | Trophic State Index Values | Chla ($mg \cdot m^{-3}$) | Trophic State Index Values | Chla ($mg \cdot m^{-3}$) | Trophic State Index Values |
| 2.0 to 5.0 | 2.6 to 6.4 | 4.0 - 5.0 | 2.9 to 5.6 | 5.0 - 10.0 | 2.0 to 5.0 | 3.0 - 4.0 |
| Variables Used: | | | | | | |
| Chla | Chla | | Chla | | Chla | |
| SD | SD | | SD | | SD | |
| TP | TP | | TP | | TP | |
| TN | | | Primary Production | | TN | |

Carlson's index is based on European and North American lake data – spring TP and summer Chla.
Chapra's index is based on spring, summer and autumn data from the Great Lakes.
Burns et al's index is based on annual average data from 24 NZ lakes.

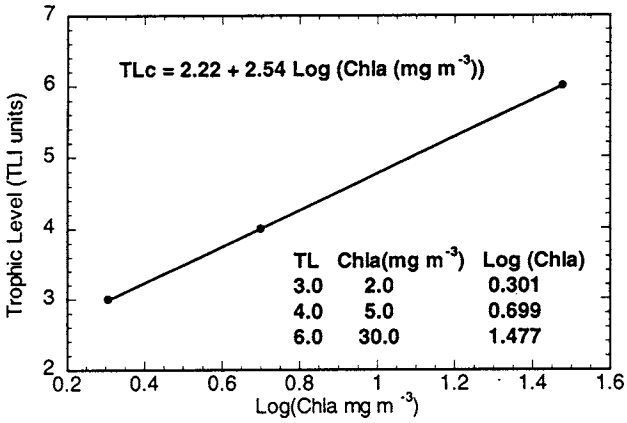



**Figure. 4.–Plot of Log Chlorophyll *a* values against the proposed Trophic Level Index values, with the linear fit to the points and equation to the line.**

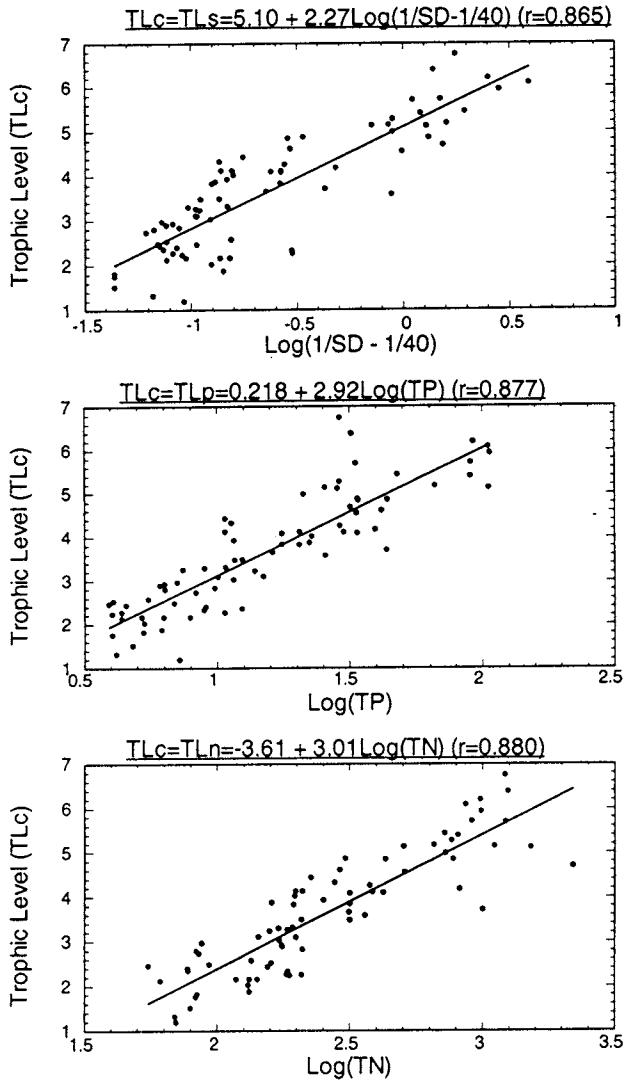



**Figure 5.–Plots of logarithms of annual average values of secchi depth (a), total phosphorus (b), and total nitrogen (c) against the trophic level index values of the chlorophyll *a* annual average obtained from the same lake in the same year.**

to a Chla concentration of 31.0 mg $m^{-3}$. Eqn (1) was then used to calculate the annual trophic level index value, TLc, from the annual average of the measured Chla concentrations for each lake each year.

Before the other variables (SD, TP and TN) can be used in the trophic state index, they must be normalised so that they can vary over the same range as the index, TLc. This was accomplished by deriving regression models between the trophic index for Chla, namely TLc, and TP, TN and SD. Annual average values were used to derive these regressions. Data from all the lakes were combined and the data were log transformed prior to analysis. After examining different types of relationships, it was found that TLc vs log (SD, TP, TN) produced the most stable relationships. The regressions are shown in Fig. 5 for 75 annual averages each for SD, TP, TN, for 24 lakes (23 NZLMP lakes plus Lake Taupo from 1995 to 1997, *pers. comm.* M. M. Gibbs) against 75 equivalent TLc values. 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 world's clearest lakes has an average SD of close to 40 m, so this value was used to allow for absorption by water. The regression equations from Fig. 5 are;

$$TLs = 5.10 + 2.27\ log(1/SD - 1/40) \quad (2)$$

$$TLp = 0.218 + 2.92\ log(TP) \quad (3)$$

$$TLn = -3.61 + 3.01\ log(TN) \quad (4)$$

In each lake for each year, these regression equations were used to calculate the trophic level indices TLs, TLp and TLn from the annual average of variables SD, TP and TN. Annual averages are used because this effectively deseasonalises the data. The assumption underlying this normalisation is that on average,

$$TLc = TLs = TLp = TLn \quad (5)$$

Indeed the average values of TLc, TLs, TLp and TLn, calculated from the regression equations, all equalled 3.66 tli units. Each of the trophic level indices is a continuous variable in the range 0-7. We assume that the values 1, 2, 3, 4, 5 and 6 define the boundaries between different trophic levels. For example, a lake with a TLc = 3.2 has a lower trophic level than another lake with TLn = 4.1.

Table 3 illustrates the application of this procedure. If necessary, values of the trophic level variables can be calculated for TLI levels of 8 or higher although this is not done here. The main reason for developing Eqn. 5 is that it normalises the trophic level indices calculated from the SD, TP, and TN. This enables the average trophic level index to be calculated:

$$TLI = 1/4\ (\ TLc + TLs + TLp + TLn) \quad (6)$$

TLI time trend values can also be calculated (using

**Table 3.–Values of variables that define the boundaries of different Trophic Levels.**

| Lake Type | Trophic Level | Chla ($mg \cdot m^{-3}$) | Secchi Depth (m) | TP ($mg\ P \cdot m^{-3}$) | TN ($mg\ N \cdot m^{-3}$) |
|---|---|---|---|---|---|
| Ultra-microtrophic | 0.0 - 1.0 | 0.13 - 0.33 | 33 - 25 | 0.84 - 1.8 | 16 - 34 |
| Microtrophic | 1.0 to 2.0 | 0.33 - 0.82 | 25 - 15 | 1.8 - 4.1 | 34 - 73 |
| Oligotrophic | 2.0 to 3.0 | 0.82 - 2.0 | 15 - 7.0 | 4.1 - 9.0 | 73 - 157 |
| Mesotrophic | 3.0 to 4.0 | 2.0 - 5.0 | 7.0 - 2.8 | 9.0 - 20 | 157 - 337 |
| Eutrophic | 4.0 to 5.0 | 5.0 - 12 | 2.8 - 1.1 | 20 - 43 | 337 - 725 |
| Supertrophic | 5.0 to 6.0 | 12 - 31.0 | 1.1 - 0.4 | 43 - 96 | 725 - 1558 |
| Hypertrophic | 6.0 to 7.0 | >31 | <0.4 | >96 | >1558 |



OLS regression) for either the individual values of TLc, TLs, TLp or TLn or for the average TLI from Eqn. 6. These procedures give the change in the TLI in TLI units per year with a p-value calculated for the slope of the regression line as shown in Fig. 6 for Lake Okareka.

# Results

Table 4 is a summary of the temperature results. They are consistent with all the lakes reporting the same type of change, as might be expected with a climatic change operating over the whole country. The average temperature change observed was $0.35° \pm 0.12°C$ per year, indicating that the analytical technique used to calculate temperature trends gives consistent results. The determination of the time trend in temperature in the lakes is relatively unimportant from the point of view of changes in the trophic state of the lakes. However, it is important in that it indicates that the deseasonalising techniques used are sensitive in observing a relatively small degree of change in data that has a large annual variation.

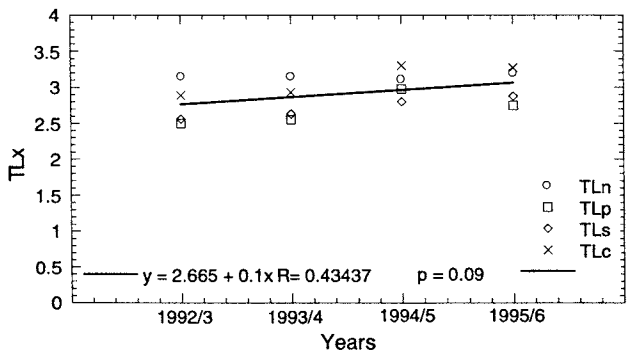



**Figure 6.–Plot of TLx values against Years with an OLS regression fit to determine the TLI time trend line for Lake Okareka.**

## *Results of Trophic State Assessment*

Table 5 shows the results of the PAC assessments of the 17 lakes with 3 or more years of monitoring data. The p-values of the PAC averages are seen to vary quite markedly, with the lower p-values indicating which lakes have probably changed with time. The PAC average and its standard error gives an idea of the magnitude

**Table 4.–Observed trends of change with time in New Zealand lake epilimnion temperatures, Feb 1992 to June 1996.**

| Lake | Change in Temperature °C per year |
|---|---|
| <u>Shallow or Intermittently Stratified Lakes</u> | |
| Non-significant changes are in brackets | |
| Omapere | 0.42 |
| Whangape | (+0.09) |
| Hamilton | 0.31 |
| Maratoto | 0.15 |
| Rotorua | 0.3 |
| Forsyth | 0.64 |
| Alexandrina | (+0.13) |
| <u>Stratified Lakes</u> | |
| Taharoa | 0.24 |
| Pupuke | 0.33 |
| Rotoiti NI | 0.22 |
| Okareka | 0.35 |
| Okataina | 0.26 |
| Tarawera | 0.46 |
| Rotokakohi | 0.35 |
| Tutira | 0.39 |
| Brunner | (-0.06) |
| Hayes | 0.22 |
| **Average** | **0.35** |
| Std. dev. | 0.12 |

**Table 5.–Percent Annual Change (PAC) results from the assessment of all variables. Results from individual variables have been compared with the assessment for each lake to determine the effectiveness of the variable in signalling change and marked with an asterisk accordingly.**

| Lake | PAC – % Annual Change | | | | | Average PAC (%/yr) | P-Value of PAC Average | Assessment from monitoring results |
|---|---|---|---|---|---|---|---|---|
| | Chlorophyll | Secchi Depth x -1.0 | Total Phosphorus | Total Nitrogen | Dissolved Oxygen Depletion | | | |
| **Shallow or Intermittently Stratified Lakes** (*Non-significant changes are in brackets.) | | | | | | Variables giving correct signals are asterisked. | | |
| Omapere | -55* | -22.5* | -37* | -20.1* | | -34 | 0.02 | Improved |
| Whangape | -21.6* | -25.8* | -26.3* | -10.1* | | -21 | 0.01 | Improved |
| Hamilton | -10.6* | -4.8* | -10.8* | -16.8* | | -11 | 0.02 | Improved |
| Maratoto | 45 | 7.6 | (+0.3)* | -11 | | 10 | 0.45 | No Change |
| Rotorua | -10.1* | insuff. data | (+0) | -1.4* | | -4 | 0.18 | Probable Improvement |
| Forsyth | (-4.4)* | (+1.0)* | (-1.6)* | -18.8 | | -5 | 0.39 | No Change |
| Alexandrina | (+1.4) | 12.1* | 6.3* | (-2.2)* | | 5 | 0.21 | Possible Deterioration |
| **Stratified Lakes** | | | | | | | | |
| Taharoa | (-3.2)* | (+1.3)* | (-3.7)* | (-2.0)* | | 0 | 1 | No Change |
| Pupuke | 10.5 | 8.9 | (-4.0)* | -8.1 | | 2.8 | 0.56 | No Change |
| Rotoiti NI | (-5.2)* | (-3.2)* | (-1.7)* | (-1.1)* | -3.5 | -0.7 | 0.38 | No Change |
| Okareka | 9.6* | 5.7* | 7.1* | (-0.3) | (-3.8) | 4.5 | 0.08 | Definite Deterioration |
| Okataina | 4.7 | -2.8 | (+0.5)* | -5.3 | 0* | -0.63 | 0.7 | No Change |
| Tarawera | (+1.5)* | (-3.6)* | (+5.5)* | -19.4 | (-2.7)* | -3.9 | 0.37 | No Change |
| Rotokakahi | 15 | (-1.4)* | (+0.7)* | (-1.5)* | -3.4 | 2.3 | 0.51 | No Change |
| Tutira | (+2.2)* | (-3.3)* | (+0.4)* | (+0)* | (-4.2)* | 0 | 1 | No Change |
| Brunner | 32.2 | 3 | (+3.5)* | (+1.9)* | (-3.7)* | 7 | 0.33 | No Change |
| Hayes | -23.9* | (-0.7) | -6.9* | -3.6* | (+1.6) | 6.9 | 0.19 | Probable Improvement |
| no. of correct signals | 11 | 11 | 16 | 10 | 3 | | | |
| **correct signals** | **59%** | **59%** | **94%** | **59%** | **50%** | | | |

of the change which has occurred in a lake. The usefulness of a PAC value is that it expresses the results derived from the different variables in the form of a common unit. This enables the results from 4 variables (shallow lakes) or 5 variables (stratified lakes) to be combined into a single PAC average and p-value for each lake.

The results of the TLx and TLI calculations for 4 representative lakes in the study are shown in Table 6. (A report by Burns and Rutherford (1998) gives detailed results for all the monitored lakes.) The actual TLI value for a lake is calculated from the two most recent years of data for the lake. Also shown is the TLI time trend and a p-value for this trend for each lake.

Hamilton Lake is a small (54 ha), intermittently stratified lake with a maximum depth of 6 m and average depth of 2 m (Tanner et al. 1990). It showed improvement over the 4 years of monitoring, starting with a TLI of 5.3 ± 0.3 (supertrophic) in 1992/3 which had changed to 4.8 ± 0.2 (eutrophic) by 1995/6 (Table 6). In 1988, the lake changed from being

**Table 6.–Annual averages, Trophic Level Index values, and TLI trends with time for 4 representative New Zealand lakes.**

| Lake | Period | Chla ($mg \cdot m^{-3}$) | SD (m) | TP ($mg\ P \cdot m^{-3}$) | TN ($mg \cdot m^{-3}$) | TLc | TLs | TLp | TLn | TLI Average | Std. Err. TLI Av. | TLI trend units $\cdot yr^{-1}$ | Std. Err. TLI trend | P value TLI trend |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hamilton | Apr'92-Mar'93 | 23.39 | 0.89 | 33.2 | 1216 | 5.70 | 5.20 | 4.64 | 5.68 | 5.30 | 0.25 | | | |
| | Apr'93-Mar'94 | 14.26 | 1.14 | 25.4 | 1107 | 5.15 | 4.94 | 4.31 | 5.55 | 4.99 | 0.26 | | | |
| | Apr'94-Mar'95 | 15.98 | 1.09 | 28.8 | 763 | 5.28 | 4.98 | 4.46 | 5.07 | 4.95 | 0.17 | | | |
| | Apr'95-Mar'96 | 12.35 | 1.09 | 21.1 | 722 | 4.99 | 4.98 | 4.07 | 4.99 | 4.76 | 0.23 | | | |
| | Averages | 16.50 | 1.05 | 27.1 | 952 | 5.28 | 5.03 | 4.37 | 5.32 | | | | | |
| Hamilton Lake 2-year TLI value (1994/6) : TLI Timetrend (1992-6) | | | | | | | | | | 4.85 | 0.16 | -0.16 | 0.10 | 0.10 |
| Hayes | Aug'92-Jun'93 | 10.91 | 3.23 | 33.8 | 430 | 4.86 | 3.86 | 4.67 | 4.32 | 4.43 | 0.22 | | | |
| | Aug'93-Jun'94 | 5.51 | 3.82 | 33.7 | 422 | 4.10 | 3.68 | 4.66 | 4.29 | 4.18 | 0.20 | | | |
| | Aug'94-Jun'95 | 5.59 | 3.46 | 30.0 | 384 | 4.12 | 3.79 | 4.51 | 4.17 | 4.15 | 0.15 | | | |
| | Aug'95-Jun'96 | 6.39 | 3.34 | 29.0 | 376 | 4.27 | 3.83 | 4.47 | 4.14 | 4.18 | 0.14 | | | |
| | Averages | 7.10 | 3.46 | 31.6 | 403 | 4.34 | 3.79 | 4.58 | 4.23 | | | | | |
| Lake Hayes 2-year TLI value (1994/6) : TLI Timetrend (1992-6) | | | | | | | | | | 4.16 | 0.11 | -0.80 | 0.80 | 0.30 |
| Maratoto | Apr'92-Mar'93 | 13.90 | 0.77 | 28.3 | 1517 | 5.12 | 5.34 | 4.44 | 5.96 | 5.22 | 0.31 | | | |
| | Apr'93-Mar'94 | 9.45 | 0.64 | 31.7 | 2194 | 4.70 | 5.52 | 4.59 | 6.45 | 5.31 | 0.43 | | | |
| | Apr'94-Mar'95 | 43.96 | 0.71 | 32.1 | 1241 | 6.39 | 5.42 | 4.60 | 5.70 | 5.53 | 0.37 | | | |
| | Apr-95-Mar'96 | 61.20 | 0.56 | 29.0 | 1211 | 6.76 | 5.66 | 4.47 | 5.67 | 5.64 | 0.47 | | | |
| | Averages | 32.13 | 0.67 | 30.3 | 1541 | 5.74 | 5.49 | 4.53 | 5.95 | | | | | |
| Lake Maratoto 2-year TLI value (1994/6) : TLI Timetrend (1992-6) | | | | | | | | | | 5.58 | 0.33 | 0.15 | 0.16 | 0.38 |
| Okareka | Jul'92-Jun'93 | 1.84 | 9.88 | 6.1 | 175 | 2.89 | 2.56 | 2.50 | 3.14 | 2.77 | 0.15 | | | |
| | Jul'93-Jun'94 | 1.90 | 9.36 | 6.3 | 175 | 2.93 | 2.63 | 2.55 | 3.14 | 2.81 | 0.14 | | | |
| | Jul'94-Jun'95 | 2.67 | 8.22 | 8.9 | 170 | 3.30 | 2.80 | 2.98 | 3.11 | 3.05 | 0.11 | | | |
| | Jul'95-Jun'96 | 2.58 | 7.70 | 7.4 | 184 | 3.27 | 2.88 | 2.75 | 3.21 | 3.02 | 0.13 | | | |
| | Averages | 2.25 | 8.79 | 7.2 | 176 | 3.10 | 2.72 | 2.69 | 3.15 | | | | | |
| Lake Okareka 2-year TLI value (1994/6): TLI Timetrend (1992-6) | | | | | | | | | | 3.04 | 0.09 | 0.1 | 0.05 | 0.09 |

macrophyte dominated to phytoplankton dominated when the macrophytes died and released their nutrients (Tanner et al. 1990). Since that time the lake was apparently establishing a new equilibrium condition with a slow settling out of particulate material. This is seen in the improvement in the average TLI values and a drop in the organic suspended solids (Burns and Rutherford 1998). The average TLc (5.28), TLs (5.03), and TLn (5.32) values are similar but the TLp (4.37) value is comparatively low indicating that a phosphorus-limited condition prevailed in the lake. This is confirmed by the low average dissolved reactive phosphorus (DRP) concentration in the lake of 1.4 mg P $m^{-3}$ and the relatively high $NH_4$ + $NO_3$ average value of 276 mg N $m^{-3}$. The TLI time trend of $-0.16 \pm 0.1$ TLI units $yr^{-1}$ indicates an improving condition.

Lake Hayes is a stratified lake with an area of 2.03 $km^2$, a maximum depth of 35 m and average depth of 18.7 m (Livingston et al. 1986). It is one of the few larger New Zealand lakes classified as eutrophic (TLI of $4.2 \pm 0.1$). It has a comparatively low value of TLs (3.79 TLI units) because the TLc:TLs relationship for eutrophic lakes is largely set up by data from shallow lakes. Shallow lakes in New Zealand are generally more eutrophic than the deeper lakes and have fairly high concentrations of suspended materials in their waters. Lake Hayes is deep and stratifies over most of its area, preventing bottom materials from entering epilimnion waters, thus giving rise to a lower TLs value for Lake Hayes when compared to shallow lakes with similar Chla levels. The TLI time trend for this lake of $-0.8 \pm 0.8$ units $yr^{-1}$ ($p = 0.3$) gives a signal of possible improvement but a PAC value of $-6.9 \pm 4.4$ % per yr, indicates probable improvement ($p=0.19$; Table 5).

Lake Maratoto is a small lake of about 140 ha in size with a maximum depth of 7 m. It is a peat lake with stained water and showed an unusual change (Table 6) of strongly increasing TLc (Chla) values together with a small decrease in TLn (TN). Because the increase with time of the TLc was large and accompanied by a small increase in TLs, the TLI time trend was $0.15 \pm 0.16$ units, indicating an increase with a large uncertainty. This large uncertainty follows from the contradictory results of increases in TLc and TLs, with a decrease in TLn with time. These results may be the consequence of the peat fires that occurred in the catchment of Lake Maratoto in 1991, possibly liberating some essential micronutrient for the phytoplankton growth.

Lake Okareka is a stratified lake 3.46 $km^2$ in area, maximum depth 33.5 m and mean depth of 20 m (Livingston et al. 1986). Lake Okareka is becoming more eutrophic and has changed classification from being oligotrophic in 1992/3 (TLI $2.8 \pm 0.2$) to mesotrophic in 1995/6 (TLI $3.0 \pm 0.1$) with an increase in TLI of $0.10 \pm 0.05$ units $yr^{-1}$ ($p = 0.09$, Table 6) and a PAC of 4.5 % $yr^{-1}$, ($p = 0.08$, Table 5). The lake is apparently phosphorus-limited with an average TLp of 2.69 compared with 3.15 TLI units for TLn. The values of TLc, TLs, and TLp have increased slightly each year while the value of TLn has remained static.

Table 7 shows the TLI average values for the lakes monitored for three or more years plus Lake Taupo, and the change in the TLI values with time (TLI trends). The TLI time trends can be compared in a qualitative manner with their corresponding PAC average values as they are also measures of change with time. They are in agreement if the p-value of the PAC average is <0.1, confirming the value of both methods of analysis. Also, the p-value of the PAC average is usually found to be high when that of the TLI time trend is also found to be high.

Results of monthly monitoring of 17 lakes (excluding Lake Taupo) from 1992 to 1996 are the following:

- Three lakes have definitely become less eutrophic and have improved at the rates of; Hamilton $-0.16 \pm 0.1$; Omapere $-0.48 \pm 0.12$ ; Whangape $-0.3 \pm 0.07$ TLI units $yr^{-1}$.
- Two lakes i.e. Rotorua and Hayes, have probably improved.
- Eight lakes did not really change their trophic level: Forsyth, Taharoa, Pupuke, Okataina, Tarawera, Rotokakahi, Rotoititi NI and Tutira.
- Lake Okareka is deteriorating at the rate of $0.10 \pm 0.05$ TLI units $yr^{-1}$ and needs consideration of remedial measures.
- Maratoto, Brunner and Alexandrina show some evidence of increased eutrophication and should continue to be monitored.

## *Assessment of Individual Trophic State Variables*

To determine which variable was the best indicator of trophic state, the PAC value of a variable was compared with the change in a lake assessed by the use of the p-value of the PAC average (Table 5). If the single variable signalled the same change, or the lack of change as the PAC average, then the variable was marked with an asterisk as shown in Table 5. For each variable, the number and percentage of correct signals was obtained and shown in the bottom row of Table 5. TP is seen to give the best prediction of when a lake is changing or not changing, with a response of 94% correct signals. Chla, SD, TN were really equivalent, all giving about a 65% correct detectable response but

**Table 7.–Comparison of Trophic Level Index (TLI) values and timetrends with Percent Annual Change (PAC) values for 18 New Zealand lakes including Lake Taupo.**

| Lake | PAC or TLI | TLI Value TLI units | TLI Std. Err. | PAC Av. or TLI trend %/yr or TLI units/yr | Std. Err. of Avs. and trends | P value of PAC Av. or TLI trend | Conclusions about Change |
|---|---|---|---|---|---|---|---|
| Alexandrina | PAC | | | 5 | 2.9 | 0.21 | Possible |
| Alexandrina | TLI | 3.13 | 0.08 | -0.05 | 0.09 | 0.58 | deterioration |
| Brunner | PAC | | | 7 | 6.3 | 0.33 | No change |
| Brunner | TLI | 2.7 | 0.13 | 0.06 | 0.14 | 0.69 | |
| Forsyth | PAC | | | -5 | 4.8 | 0.39 | No change |
| Forsyth | TLI | 5.37 | 0.19 | -0.15 | 0.16 | 0.39 | |
| Hamilton | PAC | | | -11 | 2.5 | 0.02 | Definite |
| Hamilton | TLI | 4.76 | 0.11 | -0.16 | 0.1 | 0.1 | improvement |
| Hayes | PAC | | | -6.9 | 4.4 | 0.19 | Probable |
| Hayes | TLI | 4.16 | 0.09 | -0.08 | 0.08 | 0.3 | improvement |
| Maratoto | PAC | | | 10 | 12.1 | 0.45 | No change |
| Maratoto | TLI | 5.58 | 0.27 | 0.15 | 0.16 | 0.38 | |
| Okareka | PAC | | | 4.5 | 1.93 | 0.08 | Definite |
| Okareka | TLI | 3.04 | 0.09 | 0.1 | 0.05 | 0.09 | deterioration |
| Okataina | | | | -0.63 | 1.67 | 0.7 | No change |
| Okataina | TLI | 2.57 | 0.1 | 0.04 | 0.05 | 0.47 | |
| Omapere | PAC | | | -34 | 8 | 0.02 | Definite |
| Omapere | TLI | 4.47 | 0.17 | -0.48 | 0.12 | <0.01 | improvement |
| Pupuke | PAC | | | 2.8 | 4.3 | 0.56 | No change |
| Pupuke | TLI | 3.56 | 0.16 | 0 | 0.1 | 0.99 | |
| Rotoiti NI | PAC | | | -0.72 | 0.72 | 0.38 | No change |
| Rotoiti NI | TLI | 3.54 | 0.17 | -0.05 | 0.1 | 0.64 | |
| Rotokakahi | PAC | | | 2.3 | 3.2 | 0.51 | No change |
| Rotokakahi | TLI | 3.15 | 0.1 | 0.03 | 0.09 | 0.76 | |
| Rotorua | PAC | | | -4 | 3.1 | 0.18 | Probable |
| Rotorua | TLI | 4.33 | 0.17 | | | | improvement |
| Taharoa | PAC | | | 0 | 0 | 1 | No change |
| Taharoa | TLI | 2.54 | 0.15 | 0 | 0.1 | 0.97 | |
| Tarawera | PAC | | | -0.63 | 1.67 | 0.7 | No change |
| Tarawera | | | | | | | |
| Taupo | PAC | | | | | | No decision |
| Taupo | TLI | 2.02 | 0.09 | 0.1 | 0.08 | 0.26 | |
| Tutira | PAC | | | 0 | 0 | 1 | No change |
| Tutira | TLI | 3.77 | 0.04 | -0.04 | 0.03 | 0.12 | |
| Whangape | PAC | | | -21 | 3.7 | <0.01 | Definite |
| Whangape | TLI | 5.2 | 0.11 | -0.3 | 0.07 | <0.01 | improvement |

the DO depletion rate was relatively weak giving a 50% correct response for 8 lakes, with no value for Lakes Taharoa and Pupuke. A HVOD rate could not be calculated for Lake Taharoa because of an indeterminate amount of hypolimnetic photosynthesis in that lake, and for Lake Pupuke because of an unknown degree of mixing between hypolimnetic layers of differing DO concentration.

### *Assessment of Reservoir Data*

Lake Rotorangi is a reservoir created by damming the Patea River in New Zealand. The lake is riverine in shape being 46 km long with an average width of 130 m and average depth of 28 m. Three sampling stations were created on the lake about 20 km from each other and 4 samples per year were collected from these stations. Station L1 is sited at the head of the lake at a depth of 10 m and a lake width of less than 100 m. L2 is sited at mid-lake with a depth of 40 m. L3 is situated close to the dam wall with a depth of 45 m. The residence time of the water in the reservoir is approximately 130 days (Taranaki Catchment Board 1989). The data from the three stations were not combined and were analysed as if each station were part of a different lake. The data were quite variable, as the lake was obviously affected by flood events, and seasonal patterns were not distinct. Only one significant PAC value was calculated from the 12 sets of data (4 key variables for 3 stations); that was a -4.3% $yr^{-1}$ decrease in TN at L3. The average PAC value for L1 and L2 was 0.0 and for L3 it was -1.08 % $yr^{-1}$ with a p-value of 0.39. Thus the PAC values indicated that there was no change in the trophic level of Lake Rotorangi during the period of its monitoring.

The TLI values calculated for the three stations for the years when all four TLx values were available, are shown in Table 8. The TLx values for L1 for SD, TP, and TN are similar with an average of 4.97 tli units, which is much higher than the TLc value of 2.93 (Table 8). At L2, the TLp and TLs values are similar but much lower than TLn at 4.74 TLI units. The Tlc at L2 value is 3.10 TLI units and is higher than the Tlc value at L1. At L3, Tln (4.71) remains at a level similar to its level at L1 and L2 but the TLs and TLp are lower than their levels at L2 and L1. The Tlc, in contrast to the other TLx values, is at its highest at L3 at 3.35 TLI units and is approaching the values of TLs (3.82) and TLp (3.63) at L3.

## Discussion and Conclusions

DO depletion rates are difficult to calculate accurately from monthly monitoring data, for the reasons discussed by Burns (1995). Rates are affected by weather effects, which have to be factored out to obtain a HVOD rate that is dependent on trophic condition only. The calculations to remove weather effects are complex and require excellent data, which are not always available from the monthly vertical

**Table 8.–Trophic Level Index values calculated for Lake Rotorangi.**

| Station/Period | Chla ($mg \cdot m^{-3}$) | SD (m) | TP ($mg\ P \cdot m^{-3}$) | TN ($mg\ N \cdot m^{-3}$) | TLc | TLs | TLp (tli units) | TLn | TLI | Std. Dev. |
|---|---|---|---|---|---|---|---|---|---|---|
| L1 | | | | | | | | | | |
| 95/6 Averages | 1.8 | 0.6 | 65.0 | 715 | 2.85 | 5.54 | 5.49 | 4.98 | | |
| 96/7 Averages | 1.8 | 2.0 | 42.3 | 665 | 2.84 | 4.37 | 4.95 | 4.89 | | |
| 97/8 Averages | 2.2 | 1.4 | 35.0 | 743 | 3.09 | 4.72 | 4.71 | 5.03 | | |
| Average TLx | | | | | 2.93 | 4.88 | 5.05 | 4.97 | 4.46 | 0.30 |
| L2 | | | | | | | | | | |
| 95/6 Averages | | 2.51 | | | | 4.13 | | | | |
| 96/7 Averages | 2.28 | 2.36 | 20.8 | 508.5 | 3.13 | 4.19 | 4.05 | 4.54 | | |
| 97/8 Averages | 2.15 | 2.36 | 23.3 | 690 | 3.06 | 4.19 | 4.19 | 4.93 | | |
| Average TLx | | | | | 3.10 | 4.17 | 4.12 | 4.74 | 4.03 | 0.20 |
| L3 | | | | | | | | | | |
| 95/6 Average | 2.58 | 3.16 | 17.8 | 595 | 3.26 | 3.88 | 3.85 | 4.74 | | |
| 96/7 Average | 2.85 | 3.7 | 12 | 555 | 3.38 | 3.71 | 3.36 | 4.65 | | |
| 97/8 Average | 2.93 | 3.26 | 15.5 | 591 | 3.40 | 3.85 | 3.68 | 4.73 | | |
| Average TLx | | | | | 3.35 | 3.82 | 3.63 | 4.71 | 3.88 | 0.17 |

temperature/DO profiles. Further investigation is required to determine the optimum methods for calculating HVOD rates.

Phytoplankton species and biomass data are customarily used in considering change of trophic state. These data were collected in the NZLMP, but the analyses of results from the annual combined samples did not give definitive information on change of trophic state, even for Lake Omapere, which showed the greatest degree of change of all the lakes monitored. For this reason, phytoplankton species and biomass was not used as a trophic state indicator, as envisaged in the design of the NZLMP. Phytoplankton species and biovolume can be sensitive indicators of change but more research needs to be done on sampling frequency and relating specific species to eutrophic or oligotrophic conditions. Appropriate statistical procedures would also have to be devised to discern trends in the data. Unfortunately, funding did not permit this research to be done within the NZLMP.

The question of whether to collect samples for dissolved nutrients in the epilimnion or whether to take any hypolimnion samples, needs consideration. Since only epilimnetic Chla, SD, TP, TN and hypolimnetic dissolved oxygen profile values are used in calculating PAC and TLI values, it could be argued that these are the only variables that should be sampled and analysed. This is a valid proposition if the nature of a lake is well understood from previous sampling of epilimnetic soluble nutrients and hypolimnetic sampling of total and soluble nutrients. However, until a lake is well understood, any monitoring program should contain an element of investigative as well as monitoring sampling. Changes observed from a strictly limited monitoring program could be difficult to interpret unless there is some understanding of the limnology of a lake. Dissolved nutrient concentrations, besides having value in themselves, enable calculation of total organic nitrogen (TON) and organic phosphorus (Pdiff) values which are more directly related to the organic particles in a lake than are TN and TP values (TON = TN - $NO_3$ - $NH_3$ and Pdiff = TP - DRP). They can aid in interpreting the TN and TP data. A careful cost/benefit analysis should be done for each lake when setting up monitoring investigations to determine optimal sampling programs.

The PAC value is better to use than the TLI time trend value in deciding whether a lake has changed trophic level or not because it utilises five different variables and the data are not condensed to a few numbers before analysis. The observed and residual data plots (Fig.2B) enable one to have a good look at the actual data obtained for analysis, which is not possible when annual averages are used. However, while the PAC values give a good indication that change may be happening, it is only a relative measure and difficult to utilise. The TLI value, on the other hand, gives a clear idea of the actual state of the lake and an absolute estimate of the degree of change that a lake may be undergoing. The two indicators are most effective when used together.

Because the average of the TLc, TLs, TLp and TLn values used in the TLI scheme for the 24 lakes is the same (3.66 TLI units), it is possible to compare these values for the four different variables of a lake to learn about its nature. Lake Taupo has a low TLc value relative to its TLs, TLp, and TLn values (Table 9). This is probably due to the fact that it is larger and deeper, and has a thicker epilimnion (33 m, Gibbs pers.com.) than the other lakes in the NZLMP set. Thus, relative to the availability of nutrients in this lake, the phytoplankton could be starved of light because the thick upper mixed layer would mean that the phytoplankton could spend substantial time at depths where the light intensity is low. Lakes Brunner and Lady are situated in a heavily forested area, which stains the water draining into them (Davies-Colley et al. 1993) and are found to have relatively high TLs values (Table 9). Lake Taharoa is a lake set in a small sandy catchment and its relatively low TLp value indicates phosphorus limitation to growth (Table 9). Two other lakes, Hamilton and Maratoto (Table 6) are similar in this regard, but have relatively low TLp values because there are large areas of peat in their catchments.

Six lakes are located in the Central Volcanic Plateau area of the North Island, which is an area that contains much phosphorus rich volcanic ash (White et al. 1985). Five of these lakes, Rotorua, Okataina, Rotoiti N.I., Rotokakahi and Tarawera (Table 9) show low TLn values relative to TLp values, indicating nitrogen limitation to growth in these lakes. Lake Okareka is the sixth lake in the area but in contrast, has relatively high TLn and low TLp values. It is also the only lake of the six that shows a confirmed increasing TLI trend with time (Table 7). This lake has a number of homes with septic tanks in its catchment and leachate from these tanks may be supplying sufficient dissolved nitrogen nutrients to upset the natural nitrogen limitation to growth, causing increasing eutrophication of the lake. The volcanic soils in this area retain phosphorus but do not absorb nitrate. Hoare (1980) estimated 15 kg·$yr^{-1}$ for soluble nitrogen and zero for phosphorus as the contribution per septic tank to the nutrient load on nearby Lake Rotorua and the rates for Lake Okareka would be similar.

The results of the trophic level assessment of lakes found to be changing (Table 7) are in agreement with other factors known to be influencing these lakes. Three lakes were found to have improved. Two of

**Table 9.–Trophic level values for 4 key variables for some selected lakes.**

| Lake | Period | TLc Avg. | TLs Avg. | TLp Avg. | TLn Avg. | TLI 2 yr. Avg. | Std. Err. TLI avg. |
|---|---|---|---|---|---|---|---|
| Brunner | 1992-94 | 2.26 | 3.15 | 2.41 | 2.78 | 2.65 | 0.13 |
| Lady | 1992-94 | 2.3 | 3.91 | 3.09 | 3.29 | 3.15 | 0.22 |
| Taharoa | 1992-96 | 2.3 | 2.68 | 2.08 | 3.08 | 2.54 | 0.15 |
| Taupo | 1994-97 | 1.7 | 2.01 | 2.16 | 2.15 | 2.02 | 0.09 |
| Okareka | 1992-96 | 3.1 | 2.72 | 2.69 | 3.15 | 3.04 | 0.09 |
| Okataina | 1992-96 | 2.75 | 2.44 | 2.7 | 2.23 | 2.57 | 0.1 |
| Rotoiti NI | 1992-96 | 3.97 | 3.14 | 4.09 | 3.22 | 3.54 | 0.17 |
| Rotokakahi | 1992-95 | 3.12 | 2.94 | 3.49 | 3.00 | 3.15 | 0.1 |
| Tarawera | 1993-94 | 2.38 | 2.61 | 3.2 | 2.07 | 2.56 | 0.16 |
| Rotorua | 1994-96 | 4.75 | 3.96 | 4.8 | 3.83 | 4.33 | 0.17 |



them, Lakes Omapere and Whangape, have experienced extensive regrowth of macrophytes during the monitoring period (Champion 1995, Champion et al. 1996). This regrowth has decreased resuspension of bottom materials leading to decreased TP, TN and Chla concentrations and an improvement in the water quality of the lakes. The third lake, Hamilton Lake, had a collapse of macrophytes that led to phytoplankton blooms just prior to the start of the monitoring period (Tanner et al. 1990). Much of the improvement in this lake since then has been due to the settling out of the suspended material associated with the earlier blooms. A survey of Hamilton Lake in 1999 has recorded significant growth of macrophytes (de Winton et al. 1999). The valuable information obtained from the macrophyte surveys clearly indicates that macrophyte surveys should be part of shallow lake monitoring programmes.

Two lakes (Rotorua and Hayes) have probably improved (Table 7). In 1991, a direct input of sewage into Lake Rotorua was diverted by having it sprayed into a nearby forest, with the input only entering the lake after it had leached through the forest catchment. Thus an improvement of this lake could be expected. Lake Hayes is in a totally different catchment and is probably improving in response to improved management of its catchment, with installation of riparian strips to absorb nutrients from the water running through them before the water reaches the tributary stream to the lake. Lake Brunner may be degrading because an increased number of holiday homes are being built in its catchment.

None of the key variables can individually give reliable information of lake trophic state change when the changes are small although changes in TP, or no change in TP, seem to be good predictors of lake trophic level change (Table 5). However, when all the lake variables are considered together an accurate assessment of whether a lake has changed its trophic state or not, can be obtained. It was found that three or more variables were required to give consistent signals to indicate a clear result about change of trophic state as determined by the PAC averages. The methods presented here for quantitatively summing the effects observed in all the key variables enable the sum of results to define outcomes in a more specific manner, than if the information on each variable were considered separately.

The interpretation of the TLI results for Lake Rotorangi (Table 8) is that the water at L1 is essentially riverine in character with a low Chla value and relatively high SD and TP values because of the suspended sediment content of the water. On the other hand, the water at L3 is lacustrine (lake-like) in character with the Tlc, TLs, and TLp almost in balance with each other, indicating that the phytoplankton growth has possibly reached its full growth potential with the available phosphorus. The lower TLs at L3, which is almost in balance with the Tlc and TLp, indicates that most of the river-borne sediment has settled out. The TLn values are interesting in that they show only a small decrease between L1 and L3. Also, at L2 and L3, the TLn values are much higher than those of TLp. This indicates that TN availability is surplus to phytoplankton requirements and that phosphorus is the growth limiting nutrient. Phosphorus is diminished more by phytoplankton growth and sedimentation than is nitrogen. Nitrate levels in the lake remain high.

The equations based on New Zealand lake data to determine TLI values did not apply to the reservoir data when it was still riverine in nature at Station L1 in Lake Rotorangi. However, when this water had travelled slowly down the lake for more than 100 days at an approximate speed of 300 $m \cdot day^{-1}$, the TLI values

calculated for this water could be interpreted as those of a mesotrophic lake with the Chla, SD and TP levels in balance with each other, and having surplus available nitrogen. The TLI system for lake classification can apparently be used on reservoir data to describe the nature of the reservoir water if the water has been in the reservoir for more than 100 days. Unfortunately, Lake Rotorangi is the only set of reservoir data that has been analysed using the PAC and TLI techniques. More reservoir data should be analysed to determine the applicability of these techniques to reservoir data analysis.

The equations for transforming average annual values of the key variables into equivalent trophic level values as derived from the survey of New Zealand lakes worked well for lakes in this country. An interesting question is; to what extent do the TLI equations derived for New Zealand apply to other regions and climates? This is an important question and needs to be investigated before application of the New Zealand equations to other regions. Good concepts can be rejected if attempts are made to apply them inappropriately.

There are many different groupings of lakes such as, Florida lakes, the Great Lakes, Canadian Shield lakes and Lake District Lakes from the British Lake District. The next step in this study would be to obtain data from lakes within such regions and determine whether the New Zealand TLI equations can be used in other regions or whether new equations should be derived for the different regions.

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