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Water Quality Trends in Lake Rotomanuka North

Implications for Restoration and Management

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1 Introduction

The Northern Waikato Region has an abundance of freshwater ecosystems ranging from large peatbogs, minerotrophic wetlands, peat lakes associated with developed peatlands, and shallow riverine lakes. There are more than 40 lakes ranging in area from less than 0.01 km^2 (Lake Posa, near Koromatua) to 34.4 km^2 (Lake Waikare).

The peat lakes of the Waikato Region are concentrated around the Waikato and Waipa Districts, and Hamilton City where their association with peat formations has had a marked effect on their physical, chemical and biological nature. Dystrophic (peat) lakes are typically brownish in colour with high levels of dissolved organic substances associated with leaching from adjoining peat vegetation in the catchment. Generally mildly acidic (pH5.5 – 6.5), the bottom waters are often depleted in dissolved oxygen due to the decomposition of organic carbon.

The Waikato peat lakes form the largest collection of peat lake habitat in New Zealand and are valuable conservation refuges for many unique plant and animal species. They also represent some of the few remaining areas of wetland in the formally extensive Komakorau, Rukuhia and Moanatuatua peat bogs, as well as being important recreational areas for hunting, boating and picnicking.

Lake water quality has been monitored continuously in Lake Rotomanuka North since October 1995. Earlier water quality monitoring was undertaken sporadically during the 1980's in support of numerous research programmes underway at the time. There are generally two important aims of routine water quality monitoring programmes. To determine the productivity of the waterbody and to determine long-term changes, or "trends" in water quality conditions.

This report is the first to analyse the water quality data collected from Lake Rotomanuka North since 1995, a period over which the lake has undergone substantial change following the collapse of monospecific beds of *Egeria densa* during the summer of 1996/97.

2 Site Description

Lake Rotomanuka North is a remnant of the once larger Lake Rotomanuka. Drainage in the eastern and northern catchments, the diversion of water from the Lake Rotopiko catchment circa 1950/60, and the lowering of a formed outlet channel in 1973 resulted in a substantial lowering of water levels and the formation of two distinct waterbodies (Greenwood, 1996). Rotomanuka North is now isolated from Rotomanuka South, hydrologically linked via 10 ha of marginal wetland that formed following the lowering of the lake.

Lake Rotomanuka North is located within the Waipa District, approximately 12 kilometres north of Te Awamutu on the edge of the now largely drained Moanatuatua peat bog (Boswell *et al.*, 1985). The Lake Rotomanuka complex is Crown-owned and administered by the Department of Conservation as a Government Purpose Reserve (wildlife management). The total area of open water of the two lakes is 17.7 hectares, of which Lake Rotomanuka North is approximately 12.3 ha (Department of Conservation, 1995)

Lake Rotomanuka formed during the last glaciation some 17 000 years ago, as a result of the blocking of river valleys by silt and sand from the ancient Waikato River. Small lakes were formed behind these gravel bars (McCraw, 1967). As the New Zealand climate warmed, dense forest formed. Rushes and submerged vegetation developed as the climate became wetter and warmer. The peat rapidly deepened and spread outwards, with peat growth gradually covering the sandbars that had originally dammed the lakes. As the peat thickened, the lake waters deepened and turned dark brown and acidic as a result of leaching of humic materials from the peat (McCraw, 1967).

The Rotomanuka catchment is completely pastoral, surrounded on all sides by intensive dairy farming.

3 Methods

One sampling station was established at the deepest point of the lake (Irwin, 1982). Firstly, a Secchi depth measurement was taken and temperature and dissolved oxygen readings obtained and plotted. Depths for the bottom of the epilimnion and top of the hypolimnion were calculated and used to determine sampling depths. Isothermal, well-mixed waters generally exist in shallow lakes all year round and in almost all New Zealand lakes during the winter (Vant et al, 1987). Deep and/or highly productive lakes tend to undergo thermal stratification during summer during which a layer of warm water develops overlying colder, denser water. It is important to determine the extent of stratification as during this period the two layers of water act independently of each other often having distinct chemical characteristics (Vant et al, 1987).

Monitoring of water quality from Lake Rotomanuka North followed the method established by the New Zealand Lakes Water Quality Monitoring Programme, subsequently adopted as a Ministry for the Environment protocol (Burns et al, 2000a)

Isothermal lakes

If the lake was not stratified samples were collected at ¼ and ¾ of the maximum depth using a van Dorn sampling bottle. Two 1-litre samples were collected from the upper sampling point, collectively mixed and sub-sampled into a rinsed 1-litre sample bottle used for nutrient analysis (Burns et al, 2000a). The remainder was used for suspended sediment and chlorophyll *a* (Chla) analysis.

At the lower sampling point, a single van Dorn sample is filled for nutrient analysis. A 1-litre is adequate as no Chla samples are taken from the lower depth (Burns et al, 2000a). The position of the lower sampling point is changed if the waters are anoxic. As a rule of thumb water with dissolved oxygen (DO) of less than 0.3 g m^{-3} are considered anoxic (Vant et al, 1987). When waters are anoxic the lower sampling point is taken at the mid-point of the anoxic layer. This accommodates the inaccuracies that occur in DO meters under conditions of low oxygen.

Stratified lakes

When stratified, samples were taken from both the epilimnion and hypolimnion. The sampling of the epilimnion followed the protocol established when the upper layer of Lake Rotomanuka North was isothermal, except that the sample was collected from the mid-point of the epilimnion (mid-way between the bottom of the epilimnion and the water surface). Samples from the hypolimnion were similarly taken from the mid-point (top of the hypolimnion and the lake bottom). However, if the hypolimnion is anoxic the sample was taken from the middle of the anoxic layer.

All samples were stored on ice as soon as they were collected.

Determinants

Chlorophyll *a*, Secchi depth (SD), total phosphorus (TP), total nitrogen (TN), hypolimnetic volumetric oxygen depletion rate (HVOD) and phytoplankton species and biomass are generally accepted as the key indicators of trophic state. Additionally, dissolved reactive phosphorus (DRP), total suspended solids (TSS), volatile suspended solids (VSS), ammoniacal nitrogen NH3-N, nitrate nitrogen (NO3-N), hydrogen or hydroxyl ion activity (pH), electrical conductivity (Cond), turbidity (Turb), phosphorus difference (Pdiff) and total kjeldahl nitrogen (TKN) were assessed. RJ Hill Laboratories Ltd undertook the chemical analysis.

A 40 μm mesh net with a reducing cone was used to sample large phytoplankton and zooplankton. Ten samples were taken in April 2001 by lowering the net to depths of 3m, 5m and 8m, and raising to the surface at approximately one metre per second. The sides of the net were rinsed so that material retained is washed into the bucket at the bottom of the sampler. All samples were immediately preserved in alcohol.

A known volume of sample was enumerated in 5ml aliquots in a gridded perspex tray. Aliquots were enumerated until 300 counts were obtained, or until the entire sample was counted. Unknown animals were examined on a compound microscope and identified from body morphology.

Trend analysis

The analysis of the data for the detection of trends followed "A monitoring and classification system for New Zealand lakes and reservoirs" (Burns et al, 2000b).

Essentially, the key variables were deseasonalised as per Burns et al (2000a). Chla, TP, TN and SD were plotted as a function of time of year collected with no regard for year of collection. A polynomial curve was then fitted to the annualised data. The residual value was calculated from the observed value less the value calculated from the polynomial for its day of observation. The observed and residual data were then plotted against time and a straight line plot was added to both sets of data using ordinary less squares (OLS) regression.

Percent annual change (PAC) values were calculated from the slope of the regression and dividing the slope by the average value of the variable during the period of observation. Only PAC values calculated from significant trend lines ($p<0.05$) were considered indicative of a trend. The PAC values from Lake Rotomanuka North were added together and averaged and a p-value obtained for this average (non-significant PAC values were replaced with 0.00) (Burns et al, 2000a). Changes indicating increased eutrophication were assigned positive values and changes indicating decreased eutrophication were given negative values (Burns et al, 2000b). The decision on whether the trophic state of Lake Rotomanuka North had changed over time was made by calculating the p-value of the PAC average and interpreting the result using the scale of probabilities developed by Burns et al (2000a) (Table 1).

Table 1: Scale of probabilities devised by Burns et al (2000a) using professional judgement after analysing the results from the data of 17 monitored lakes

p-value of 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) was established for Lake Rotomanuka North following Burns et al (2000a). The annual average value for each lake were used for calculating equivalent trophic level values (TLx) for Chla (TLc), SD (TLs), TP (TLp), TN (TLn). The TLI scheme uses the following equations to determine each individual TLx value:

$$TLc = 2.22 + 2.54\log(Chla) \qquad \textit{eqn. (1)}$$
$$TLs = 5.10 + 2.27\log(1/SD - 1/40) \qquad \textit{eqn. (2)}$$
$$TLp = 0.218 + 2.92\log(TP) \qquad \textit{eqn. (3)}$$
$$TLn = -3.61 + 3.01\log(TN) \qquad \textit{eqn. (4)}$$

The assumption is held that:

$$TLc = TLs = TLp = TLn \qquad \textit{eqn. (5)}$$

Therefore the average trophic level index for Lake Rotomanuka North can be calculated by:

$$TLI = 0.25(TLc + TLs + TLp + TLn) \qquad \textit{eqn. (6)}$$

TLI trends are stated for either individual values of TLc, TLs, TLp, or TLn (equations 1-4 respectively) or for the average TLI (equation 6). Significant changes in trophic level are expressed in TLI units per year with a p-value calculated for the slope of the regression line (Burns et al, 2000b). Table 2 illustrates the application of this procedure.

Table 2: Values of variables define the boundaries of different Trophic Levels (from Burns et al, 2000b)

Lake Type	Trophic Level	Chla (mg m^{-3})	Secchi Depth (m)	TP (mg P m^{-3})	TN (mg N m^{-3})
Microtrophic	< 2.0	< 0.82	> 15	< 4.1	< 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
Hypertrophic	>5.0	>12	>1.1	>43	>725

4 Results

Table 3 shows annual epilimnion averages for measured and calculated variables for Lake Rotomanuka North from October 1995 to December 2001 including the averages for the whole period for all measured variables. Altogether, 71 water quality records were collected over this period.

Table 3: Annual and period epilimnion averages for Lake Rotomanuka North from October 1995 to December 2001 plus the averages for the whole period for all measured variables

	Date	Lake depth m	Avg Temp °C	Avg DO % sat	Avg DO $mg.l^{-1}$	CHLA $mg.m^{-3}$	Secchi depth m	TP $mg.m^{-3}$	TN $mg.m^{-3}$	Pdiff $mg.m^{-3}$	TKN $mg.m^{-3}$	NH4 $mg.m^{-3}$	NNN $mg.m^{-3}$	DRP $mg.m^{-3}$	pH	Cond $mS.m^{-3}$	Turb NTU	SS $g.m^{-3}$
Average	Oct95-Dec 95	1.70	19.25	88.2	8.15	17.50	3.24	15.33	673.67	13.00	633.33	23.33	40.33	2.33	6.97	16.47	2.73	2.17
Std dev		0.36	1.04	0.34	0.26	1.70	0.71	0.62	38.50	1.42	81.56	8.16	43.06	2.04	0.07	0.31	0.99	1.51
Average	1996	2.04	16.52	81.6	7.63	18.75	2.73	25.50	766.33	22.79	625.00	22.50	141.33	2.71	7.19	16.03	2.53	3.84
Std dev		0.72	4.92	1.26	1.42	9.14	0.83	16.34	129.70	17.36	100.70	12.33	123.95	2.38	0.16	0.54	0.64	2.25
Average	1997	1.79	15.47	80.3	7.95	13.44	1.89	21.25	701.00	18.09	675.45	65.00	25.55	4.00	7.23	16.21	2.99	3.64
Std dev		0.70	4.69	1.18	0.96	4.91	0.60	5.21	78.95	3.63	57.13	53.81	37.40	3.41	0.23	0.59	0.99	2.26
Average	1998	1.92	18.40	88.1	8.26	24.73	1.37	33.27	847.36	30.18	791.82	58.18	55.55	3.09	7.28	16.19	4.02	9.18
Std dev		0.87	4.26	1.68	1.34	10.84	0.44	11.58	150.07	11.70	101.07	55.02	87.33	2.49	0.27	1.28	1.15	5.38
Average	1999	1.62	18.59	85.9	8.09	17.00	1.51	27.50	842.70	23.50	837.00	32.00	16.27	4.00	7.29	17.11	3.96	5.70
Std dev		0.53	4.65	0.80	0.85	7.59	0.21	7.56	239.50	7.13	70.43	44.40	38.03	5.60	0.37	0.35	0.97	1.12
Average	2000	1.66	17.22	76.2	8.06	17.73	1.15	32.50	843.55	29.91	813.33	65.45	22.64	2.18	7.21	18.25	4.42	6.27
Std dev		0.41	4.32	1.73	2.04	9.28	0.21	9.13	130.85	9.23	132.87	63.33	29.99	0.57	0.29	0.48	0.98	1.57
Average	2001	1.25	17.54	83.0	8.03	16.20	1.53	32.78	798.80	27.70	777.00	26.50	21.80	2.40	7.51	18.15	3.76	5.80
Std dev		0.49	4.42	1.62	2.17	6.48	0.28	13.40	119.97	14.33	99.07	26.44	42.96	1.34	0.19	1.28	0.79	1.21
Average	Oct95-Dec01	1.72	17.34	83.0	8.01	18.15	1.78	26.88	793.28	24.77	745.51	44.12	48.62	3.02	7.27	16.94	3.57	5.55
Std Dev		0.61	4.47	1.49	1.59	8.58	0.59	11.91	153.60	12.30	108.09	46.54	77.05	2.95	0.26	1.08	1.06	3.30

Notes:
Avg = average; DO = dissolved oxygen; Chla = chlorophyll *a*; TP = total phosphorus; TN = total nitrogen; DRP = dissolved reactive phosphorus; Pdiff = TP minus DRP; TKN = total kjeldahl nitrogen; NH4 = ammonium; NNN = total oxidised nitrogen; Cond = electrical conductivity; Turb = turbidity; NTU = nephelometric turbdity units; SS = suspended sediment; Std Dev = standard deviation.

Plots of the key variables as a function of the month of collection with no regard for the year of collection show little seasonal patter (Figure 1). Though in keeping with Burns et al (2000b) a polynomial curve was fitted and the residuals for each variable calculated (Figure 2). Except for TN, the slopes and pattern of variability between the observed and residual data for each of the key variable where quite similar indicating that seasonality was not an important determinand.

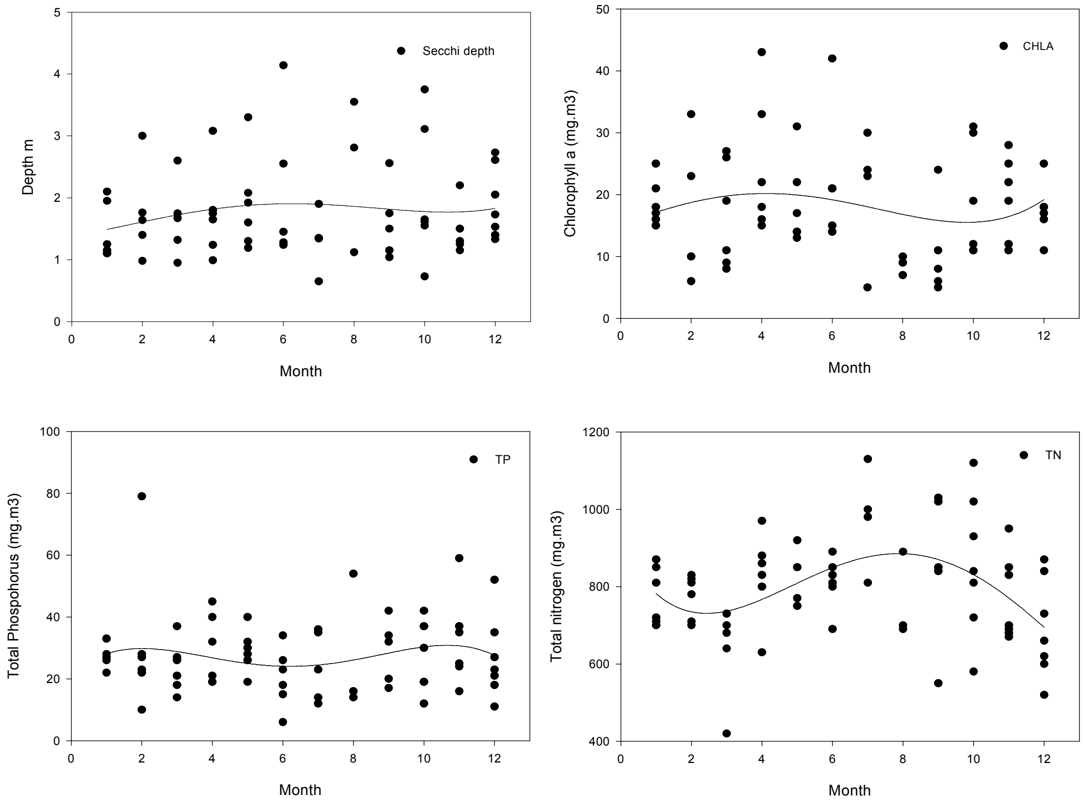
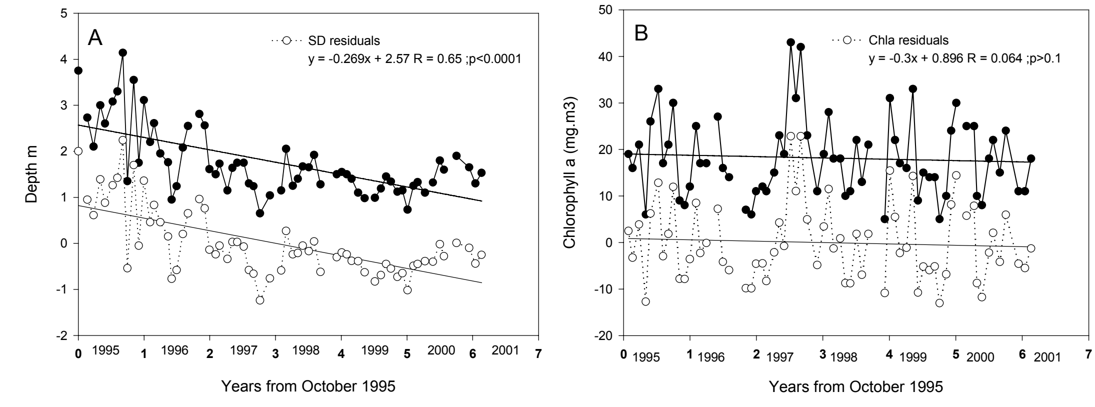


Figure 1: Plot of the key variables as a function of month of collection from Lake Rotomanuka North fitted with a polynomial curve. A.= SD; B.= Chla; C.=TP; D.=TN



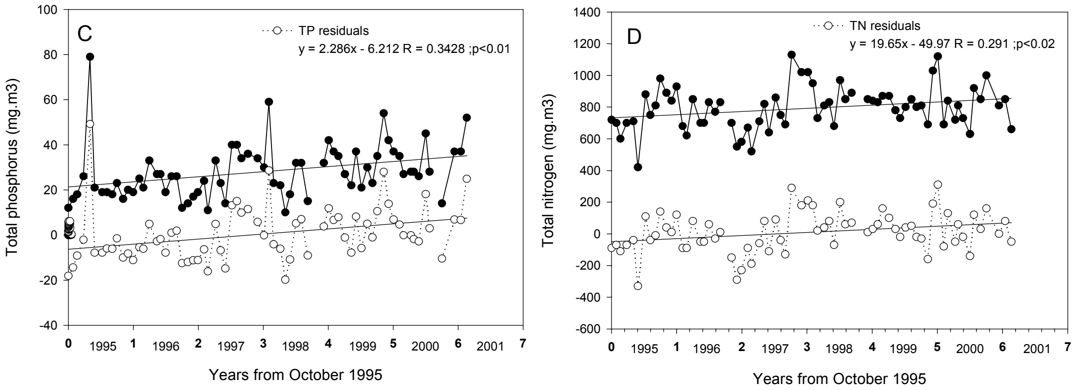


Figure 2: Plots of time trend residuals after deseasonalising observed data from Lake Rotomanuka North. A.= SD; B.=Chla; C.=TP; D.=TN. (• - closed symbols are observed data)

Analysis of DO and temperature data showed that while stratification did occur consistently in Lake Rotomanuka North during the summer months the level and extent of the thermocline varied markedly making the calculation of the HVOD difficult.

Table 4 shows the annual change values for the 1995 to 2001 period demonstrating there was a significant decline in SD of 0.27 m per year and a significant increase in TP and TN of 2.28 and 19.65 mg^{-3} per year respectively. This equates to PAC values of 15.2%, 8.4% and 2.5% respectively. Chla showed a non-significant trend over the corresponding period.

Table 4: Percentage annual change values of the key variables and related information.

	Chl*a*	**SD**	**TP**	**TN**
Annual change	(-0.3)	-0.27	2.28	19.65
Unit	(mg m^{-3} year^{-1})	(m year^{-1})	(mg m^{-3} year^{-1})	(mg m^{-3} year^{-1})
p-value	p<0.61	p<0.0001	p<0.01	p<0.02
Period average	18.15 (mg m^{-3})	1.78 (m)	26.88 (mg m^{-3})	780 (mg m^{-3})
PAC (%/year)	(-1.6% year^{-1}) = 0	15.2% year^{-1}	8.4% year^{-1}	2.5% year^{-1}
Average PAC	6.5% year^{-1} with a p-value = 0.15			

Notes:
The p-value of each annual change value gives the probability that the slope of the regression line is not 0, or that there is a statistically significant (p<0.05) linear relationship between the two variables
The p-value of each PAC average gives the probability that the calculated PAC average could be obtained by chance when its value is zero.
Non-significant changes are in brackets.

Overall there was a probable change in the average PAC value of 6.5% (p-value = 0.15).

The average TLI value for Lake Rotomanuka North over the observed period was 4.85, rising at a rate of 0.08 ± 0.22 units year^{-1} ;p<0.05 (Figure 3). The TLI is an aggregation of the four key variables and is similar to the trend analysis results obtained using the PAC calculations except that in this case the TLn trend is non-significant.

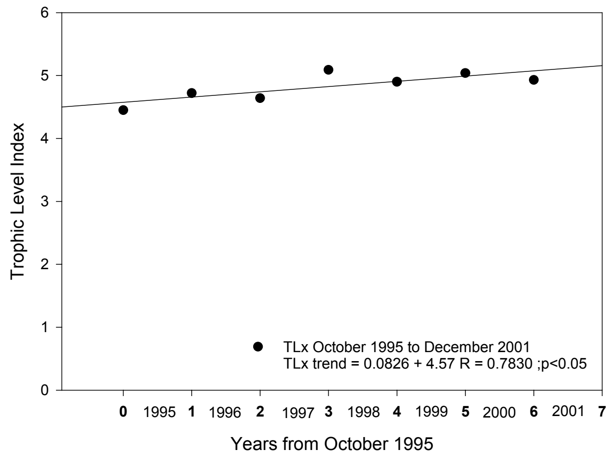


Figure 3: Plot of Lake Rotomanuka North trophic level index against the sampling period with an Ordinary Least Squares (OLS) regression fit to determine the TLI time trend line.

Closer examination of the TLx for individual variables shows a significant increase in trophic level of 0.157 year^{-1} ;p<0.05 and 0.021 year^{-1} ;p<0.02 for TLs and TLp respectively (Table 5). TLn and TLc do not show significant trends despite TLn having a significant PAC trend.

Table 5: Annual average values for four key variables from Lake Rotomanuka North with corresponding TLx and TLI values for the period October 1995 to December 2001.

Period	Chla (mg m^{-3})	SD (m)	TP (mg m^{-3})	TN (mg m^{-3})	TLc	TLs	TLp	TLn	TLI avg	Std Er TLI
Oct 95-Dec 95	17.5	3.24	15.3	673	5.38	3.86	3.68	4.90	4.45	0.41
1996	18.7	2.73	25.5	766	5.45	4.04	4.33	5.07	4.72	0.33
1997	13.4	1.89	21.2	701	5.09	4.43	4.09	4.96	4.64	0.23
1998	24.7	1.37	33.2	842	5.76	4.75	4.66	5.20	5.09	0.25
1999	17.0	1.51	27.5	777	5.35	4.65	4.42	5.20	4.90	0.21
2000	17.7	1.15	32.5	834	5.39	4.94	4.63	5.20	5.04	0.16
2001	16.2	1.53	32.8	798	5.29	4.65	4.64	5.13	4.93	0.17
Averages	18.1	1.78	26.9	780	5.42	4.48	4.39	5.12	4.85	0.25
TLI Trend (units year^{-1})					-0.004	0.157	0.137	0.041	0.082	
p-value					>0.1	<0.05	<0.02	<0.1	<0.05	

A TLI value is a useful means of communicating trophic state to the lay community as it provides an easily understandable single value upon which changes over time can be measured and comparisons between lakes made. The annual TLx value calculated for Lake Rotomanuka North classifies the lake as eutrophic. Evaluation of the TLx indices over the period of observation shows that the lake could have been classified as hypertrophic during 1998 and 2000 and at the current rate of eutrophication the lake could be consistently hypertrophic by 2004.

This is in contrast to results obtained by the Waikato Valley Authority during an assessment of the water quality of Lake Rotomanuka North between January and March 1981 and a comparative study during August 1981. The authors reported clear water with a slight peat stain and Secchi depth readings of up to 3.5 m during both summer and winter. Mean chlorophyll *a* levels were 14 mg m^{-3} during summer and 2 mg m^{-3} in August. Considering the low chlorophyll *a*, good clarity and low nutrient levels (average TP and TN were 17 and 703 mg m^{-3} respectively) the authors concluded the lake was best described as mesotrophic (Boswell et al, 1981). The Boswell, et al (1981) results should be treated with caution as conclusions are drawn from only a 2 month data record.

The TLp value at 4.39 is lower than the TLn value at 5.12, indicating that Lake Rotomanuka North is phosphorus-limited in relation to phytoplankton growth some of the time. Figure 4 appears to indicate that TP has increased at a faster rate during the observation period than TN. The TN:TP ratios show a significant downward trend ($p<0.05$) between 1995 to 2001.

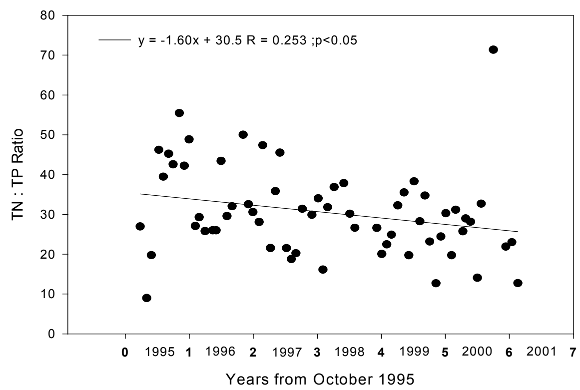


Figure 4: TN:TP ratios of observed data from Lake Rotomanuka North between October 1995 and December 2001.

Chlorophyll *a* concentrations within Lake Rotomanuka North have remained constant throughout the observation period despite an increase in TN and TP and a significant decline in water clarity. Though the chlorophyll *a* levels are high these may not be indicative of a high cell biomass as the concentration of Chla within phytoplankton vary depending on body mass and species (Pridmore, 1984).

It is generally expected that an increase in soluble nitrogen and phosphorus in the lake would result in a corresponding increase in plant biomass. Given that the lake is now completely devoid of submerged macrophytes (Clayton, J pers. comm.) that expected increase should manifest itself in an increase in phytoplankton biomass. Figure 5 illustrates what proportion of the lake Secchi depth can be accounted for by algal production. As a ratio of the light attenuation effects of phytoplankton versus the estimated beam attenuation coefficient, the figure shows that the influence of phytoplankton on water clarity has decreased significantly overtime, to the extent that algal production accounts for only a small proportion of total water clarity. The light attenuation effect (Cphyto) was estimated from a table derived from Davies-Colley et al (1993) and is given as

$$Cphyto = 0.33\,Chla^{0.65} \qquad \textit{eqn. (7)}$$

The beam attenuation effect (C) was estimated from Davies-Colley et al (1993) as

$$C = 6.4/SD \qquad \textit{eqn. (8)}$$

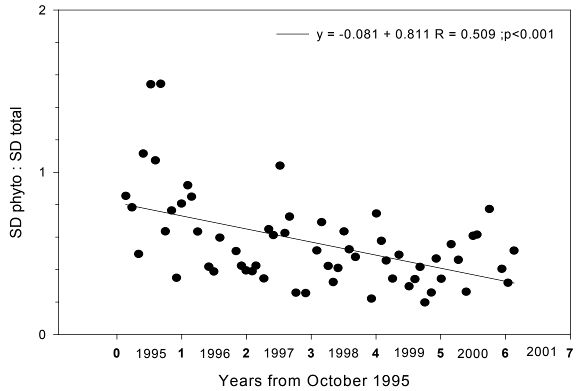


Figure 5: Relationship between the light attenuation effects of live algae against the estimated beam attenuation coefficient as a means of estimating the contribution of phytoplankton to the water clarity of Lake Rotomanuka North.

To confirm the decline in the water clarity of Lake Rotomanuka North a plot of suspended sediment over the observed period was made (Figure 6). An OLS regression was that undertaken on the observed data as a plot of the deseasonalised residual data showed no apparent seasonal variation. A significant trend in the observed data was confirmed ($p<0.001$). The data confirms that there has been an increase in the amount of suspended sediment within the water column and that a large majority of this material is not algal biomass but rather some other form of suspended matter.

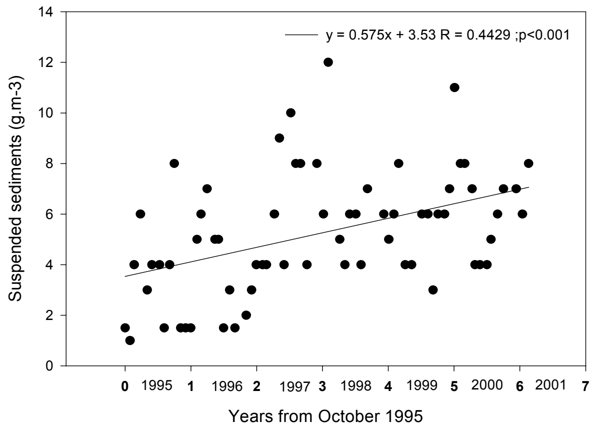


Figure 6: Plot of time trend suspended sediment observed data from Lake Rotomanuka North between October 1995 to December 2001.

During the present study the phytoplankton of Lake Rotomanuka North were numerically dominated by the diatom *Cyclotella* sp. (Class: Diatomophyceae), and

Oscillatoria sp. (Class: Cyanophyceae). Other phytoplankton taxa included *Ceratium hirundinella* (Class: Dinophyceae), *Anabena* sp. (Class: Cyanophyceae), and *Trachelomonas* sp. (Division: Euglenophycophyta). The results should be treated with a degree of caution as the data was generated from a single sampling event. A detailed species list is attached in Appendix 1.

The dominant Cladocera species in Lake Rotomanuka North were *Bosmina* spp. and *Boeckella* and *Calamoecia* the dominant copepod species. The Rotifer *Keratella* sp. were recorded in reasonably high numbers (Appendix 1).

The results of the 2001 study can be compared with a more detailed study undertaken in 1986 (Etheredge, 1987) (Table 6). Whilst no statistical comparison was made between the two sets of data there appears anecdotally to be a shift in the phytoplankton community from a dominance of small bodied Chlorophyceae's such as *Volvox* sp. and *Pediastrum* sp. to large, chain forming blue green algae such as *Oscillatoria* sp. (Class: Cyanophyceae). The small bodied diatom *Cyclotella* sp. was recorded in high abundance during both studies.

Table 6: Comparison of the numerical dominance of phytoplankton taxonomic Class's between the present study and Etheredge (1987).

Rank	Etheredge (1987)	Current study
1	Chlorophyceae	Diatomophyceae
2	Diatomophyceae	Cyanophyceae
3	Euglenophyceae	Chlorophyceae
4	Zygophyceae	Euglenophyceae
5	Cyanophyceae	

Notes:
Class of phytoplankton ranked in order of numerical dominance from highest (1) to lowest (5).

Comparing the results of the 1981 Waikato Valley Authority survey with the current study suggests a change in phytoplankton abundance. The study found low phytoplankton counts were characteristic with chlorophyll *a* concentrations exceeding 30 mg m^{-3} on only one occasion. The main algal species were *Trachelomonas* sp., *Cryptomonas* sp., and *Peridinium* sp. (Boswell et al, 1981).

5 Discussion

Rotomanuka North is a shallow, weakly stratified, eutrophic lake. The levels of key nutrients (TN and TP) are high and are reflected in high algal biomass and low water clarity. The trophic status of the lake has increased significantly over the observed period.

The lake has likely undergone progressive eutrophication as the catchment was converted from native terrestrial and wetland vegetation to agricultural landuses. Typically, peat lakes adjoining ombrogenous peat bogs were oligotrophic with high levels of dissolved organic matter and mildly acidic. Over time Lake Rotomanuka North has changed from a low nutrient status to mesotrophic (Boswell et al, 1981) to eutrophic.

Cooke et al (1993) consider the most obvious, persistent, and pervasive water problem is that of eutrophication, linked principally to the discharge of contaminants from agricultural, industrial and urban catchments. The small shallow lakes of the Waikato Region are no exception having deteriorated through excessive additions of plant nutrients, organic matter, and silt, which combine to increase algal biomass, reduced water clarity and possible decreased lake volumes (Champion and Shaw, 2000). Similarly, the agricultural conversion of the Lake Rotomanuka North catchment is likely to have affected its water quality.

Intensive dairy farming has been the dominant catchment landuse around Lake Rotomanuka North during the latter half of the 20th century and has changed little since the 1980's. The exception has been the implementation of regulatory controls on dairy shed effluent treatment and disposal which has resulted in all farms within the catchment operating land-based treatment systems. The last farm converted from a two-stage oxidation pond to land treatment upon the expiration of their discharge consent in June 2001 (Watson, D. pers. comm.)

There are few drains directly flowing into Lake Rotomanuka North and those that do are consistently short (Greenwood, 1996). Most inputs of water to the lake are believed to be via diffuse surface flows, groundwater and rainfall. The nutrient levels of the surface and groundwater inputs have not been directly measured though information from other catchments in the Waikato Region suggests these inputs are high in soluble nitrogen and phosphor (Wilson & Smith, 2001).

Of particular interest is the high TN:TP ratio in the lake observed at the start of the study. The low levels of phosphorus relative to nitrogen show that P may be the limiting nutrient within the lake. This is supported by research undertaken by Pridmore et al (1985) who found TN:TP ratios of 59, the highest recorded out of 12 North Island lakes sampled. The ratio of nitrogen to phosphorus is similar to those encountered in highly eutrophied Northern Hemisphere lakes where a superabundance of nitrogen exists in the catchment (Vant, N. pers. comm.). Large nitrogen losses occur from intensively farmed catchments with little riparian margins, developed wetlands and extensive networks of tile drains, a similar situation in many ways to the Lake Rotomanuka catchment.

A typical dairy farm oxidation pond has TN:TP ratios of 5, which is enriching in P relative to N (Hickey et al, 1989). It is reasonable to expect that with direct inputs of oxidation pond effluent to Lake Rotomanuka North as has occurred until recently, the ratio of TN:TP would decrease over time. The rate of decrease would be a factor of the amount of treated effluent discharged and the amount of nitrogen discharged from other sources.

The interesting question is whether an increase in the trophic level index, confirmed in the PAC analysis, is indicative of eutrophication in the traditional sense or rather that an increase in plant nutrients has not resulted in an increase in biological productivity as evident with the static chlorophyll *a* levels. It is speculated that the decrease in water clarity and increase in total nitrogen and phosphorus is a consequence of the collapse of the macrophyte beds (dense monospecific stands of *Egeria densa*) that occurred in the summer of 1996/97. The resulting pulse of organic material that occurred following microbial decomposition of the plant biomass released large amounts of organic nitrogen and phosphorus that for some reason remains largely bio-unavailable.

The collapse of the macrophyte beds is also likely to have influenced the change in the phytoplankton assemblage observed within the lake. There appears to have been a shift from small-bodied algae (*Volvox* sp. and *Gymnodium* sp.) to either large cellular organisms or those that form long multicellular chains. It is further speculated that this change is a result of a decrease in the population of large bodied zooplankton such as *Daphnia* sp. which prior to the collapse were able to find suitable refugia in the macrophyte beds. Upon their collapse *Daphnia* were exposed to predation from zooplanktivorous smelt (*Retropinna retropinna*). Smelt are visual feeders and are less efficient at eating small-bodied zooplankton such as the Rotifer (*Keratella* sp.). The open nature of the lake system and the lack of piscivores encourage the abundance of zooplanktivores. A dominance of small-bodied zooplankton result and a corresponding shift in the abundance of inedible large, chain forming phytoplankton (*Oscillatoria* sp., *Anabena* sp., *Microcystis* sp., & *Cyclotella* sp.) and/or cyanobacteria is apparent.

In the context of state of the environment reporting a healthy shallow lake is dominated by aquatic macrophytes in a stable clear water state. There are allied communities of fish and invertebrates that operate in equilibrium (Moss, 1996). A shallow lake that is considered degraded by nutrient enrichment is dominated by algal communities; diatoms, green algae, dinoflagellates and blue-green algae. This second state, equally stable, is less species rich and less diverse, with depauparate fish and invertebrate communities and an absence of submerged aquatic flora (Scheffer et al, 1994).

Moss (1996) proposes the Alternative Stable State model by which he contends that both algal and macrophyte dominated communities can exist in a wide range of nutrient loadings. Switch mechanisms are promoted which encourage the movement from one state to the other. In Lake Rotomanuka North the macrophyte collapse may have been due to increased nutrient loadings prior to 1995, excessive macrophyte biomass resulting in extended periods of root-sediment anoxia, or from a general senescence that appears prevalent in *Egeria densa* and which has been observed in other lowland Waikato lakes (Champion P, pers. comm.).

The re-establishment of the macrophyte flora is considered desirable however several buffers may prevent this from occurring in the short to medium term. The high dissolved organic matter and high phytoplankton biomass in the lake is likely to have reduced the light climate to the extent that germination of macrophyte propagules from the seed bank is restricted. Further, the large amount of organic material covering the bottom sediments may be preventing those seeds that do germinate from emerging from the sediment (de Winton, M. pers. comm.). Additionally, biotic disturbance from benthic fish such as brown bullhead catfish (*Ameriurus nebulosus*) may also restrict macrophyte re-establishment.

NIWA is currently undertaking an *in-vivo* assessment of the viability of the seedbank community at the lake, the results of which are expected by the end of 2002 calender year.

A large body of work has been developed in the Northern Hemisphere on shallow lakes that did not respond to traditional manipulation techniques involving the reduction in external nutrient loading. Biomanipulation is a term coined by Shapiro et al (1975) and refers to manipulation of the fish community to reduce predation pressure on herbivorous zooplankton., supposedly followed by an increased abundance and size of zooplankton, particularly *Daphnia* (Hansson et al, 1998). This in turn leads to higher grazing pressure on phytoplankton and, subsequently to clear water.

In Lake Rotomanuka North this would involve the control of the smelt and catfish population as well as a reduction in the population of herbivorous rudd (*Scardinius erythrophthalmus*).

While in theory a reduction in the fish population may reduce the phytoplankton biomass in Lake Rotomanuka North the high level of organic matter reducing water clarity is of particular concern. Reduction in phytoplankton biomass following biomanipulation may not increase water clarity if the levels of organic material remain high. Further investigation to the possible causes is recommended.

6 Conclusion

The collection and analysis of water quality data is an important tool in assessing the ecological condition of lakes and compliments ecological studies on fish, invertebrate and plant communities. Trend analysis using proven statistical methods provides a powerful tool to determine whether a waterbody is improving, degrading or has remained unchanged.

Lake Rotomanuka North is a small, shallow nutrient rich lake that has undergone progressive cultural eutrophication since catchment development and land use intensification. The lake is now classified as eutrophic with a trend towards a hypertrophic classification.

Though the concentration of plant nutrients have increased since the last water quality measurements were taken in the early 1980's, there does not appear to be a corresponding increase in the chlorophyll a concentrations in the lake. Organic nitrogen and phosphorus compose a large percentage of total nutrients in the lake and it appears that it is these fractions of N and P that have increased in the lake. The concentration of bio-available nitrate and DRP has remained unchanged through the observation period.

A decreasing ratio of TN:TP suggests an influence of dairy shed effluent on the external nutrient loading to the lake. The discharge of effluent to water within the Rotomanuka catchment has now ended following the expiration of the discharge permits. All dairy shed effluent within the catchment is now disposed of via land treatment.

The collapse of *Egeria densa* could have contributed to the high levels of dissolved organic matter in the lake. The high levels that remain could be preventing re-establishment of aquatic macrophytes by restricting the amount of light penetrating the bottom sediments. Additional mechanisms preventing re-establishment include smothering of the seed bank by large amounts of settled organic material and the bioturbation effects from benthic fish such as catfish.

Biomanipulation of the fish population could increase the population of large-bodied zooplankton, which as efficient grazers, can promote clear water by controlling phytoplankton numbers. The success of such a restoration technique requires the control of other factors influencing the water clarity of Lake Rotomanuka North such as the high levels of organic matter.

It is recommended that water quality monitoring of Lake Rotomanuka North be continued so that changes in lake trophic state are monitored and the trends of key variables determined

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Appendix 1

Table 7: Species abundance (number of individuals per litre) of phytoplankton and zooplankton collected from Lake Rotomanuka North on 24 April 2001.

	Species/L		
	3m	**5m**	**8m**
Phytoplankton			
Cyanophyceae			
Microcystis colony	5.0	5.3	1.9
Oscillatoria	552.5	269.7	209.1
Anabena	62.8	3.0	9.4
Diatomophyceae			
Cyclotella	627.9	316.4	113.2
Dinophyceae			
Ceratium hirundinella	80.4	10.5	9.4
Gymnodinium	0.5	0.0	0.0
Euglenophyceae			
Euglena	0.5	0.0	0.4
Trachelomonas	0.0	10.5	0.0
Chlorophyceae			
Volvox	45.2	7.5	15.6
Pediastrum	0.8	0.0	0.0
Zooplankton			
Cladocera			
Bosmina sp.	52.7	31.6	20.9
Daphnia sp.	4.5	0.0	0.0
Ceriodaphnia sp.	0.5	0.0	0.0
Copepoda			
Calanoidea			
Boeckella sp	3.0	9.9	4.7
Calamoecia sp	5.0	6.0	3.6
Calanoid juvenile	0.0	3.0	0.5
Copepod nauplii	0.0	7.5	10.4
Cyclopoida	0.0	0.0	0.1
Rotifera			
Keratella procurva	113.0	62.5	41.4
Trichocerca sp.	1.5	0.0	1.4
Scaridium sp.	2.8	0.2	0.0
Synchaeta sp.	0.5	0.0	0.0
Platyias quadricornis	0.5	0.0	0.0
Filinia sp.	0.0	0.0	0.1
Rhizopoda			
Arcella sp. I	51.5	0.0	0.2
Arcella sp. II	0.5	0.0	0.5
Centropyxis sp.	0.8	0.0	0.9
Netzelia tuberculata	0.0	0.0	0.2