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Review of the Waikato Regional Council shallow lakes indicators project

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Executive summary

This report was commissioned by the Waikato Regional Council to provide an independent review of the Waikato Regional Council shallow lakes indicators project. The primary objectives of this review were to determine:

1. Whether shallow lake indicators as used currently are appropriate for the purposes of evaluating lake health and effectiveness of management activities.

2. Whether the frequency of monitoring as currently employed is sufficient for these purposes.

3. Whether additional indicators exist that should be investigated for future monitoring purposes.

The Waikato Regional Council currently has two monitoring programs: (i) the Waikato shallow lake indicator program for which several lakes are sampled three times between December and the following May, and (ii) a trophic state monitoring program of eight lakes at up to monthly frequency.

The variables monitored included: temperature, dissolved oxygen, dissolved reactive and total phosphorus, dissolved inorganic nitrogen species and total phosphorus, chlorophyll *a* and suspended solids, macrophyte surveys, and zooplankton. Trophic state indicators are generally reported as trophic level index (TLI) according to Burns et al. (1999) and the zooplankton data are reported as the Rotifer TLI according to Duggan et al. (2001).

Analysis of variability of the eight lakes with long term data has shown that indicators used for the shallow lakes in the Waikato Region have high inherent background variability, making it difficult to detect water quality trends. The sampling frequency in the Waikato shallow lakes indicator program is inadequate to accurately determine the mean value of variables for the monitoring period (i.e. December, March and May). The sampling period between December and May does not necessarily reflect the period of highest productivity of the year and trophic state indicators can be up to two orders of magnitude higher outside this six month period.

The Rotifer TLI, which is monitored concurrently with the TLI, was significantly correlated with the TLI, however, the regression residuals showed discrepancies up of to two TLI units and the slope of the regression between the two variables suggested that there may be more consistent differences between the two variables at low TLI values in the Waikato lakes; the Rotifer TLI was developed including Rotorua lakes which are generally considerably deeper than those in the Waikato region.

There was no strong evidence of alternate states in the Waikato lakes that show regime shifts between clear-water vegetated and turbid devegetated states. However, an analysis of the relationship of total phosphorus to turbidity showed a discontinuity that provides indirect evidence of a rapid transition in water clarity over a relatively small range of total phosphorus concentrations, with high likelihood of an association to changes in vegetation state.

Alternative indicators considered in this study were biochemical oxygen demand and phytoplankton composition and it is recommended to include both measures in the monitoring program to evaluate their potential as indicators which could ultimately be used to supplement those currently used in developing an integrated assessment of lake health.

It is recommended that it would be most valuable to keep any lake on the monitoring program with 3+ years of existing data to eventually produce a consistent long-term record for these lakes. Based on this criterion alone and irrespective of any other

monitoring programs, the candidate lakes are: Harihari, Mangahia, Maratoto, Ngahewa, Ohinewai, Okowhao, Otamatearoa, Rotomanuka, Serpentine East, Serpentine North, Serpentine South, Taharoa, Tutaeinanga, Waahi, Waikare, Whangape. It is not recommended to reduce sampling frequency in any of the lakes. To determine the state of currently unmonitored lakes, it may be reasonable to rotate a number of lakes in the sampling regime, but this number should be small in order to produce a long-term record for as many lakes as possible.

1 Introduction

Since 2006, the Waikato Regional Council has carried out water quality monitoring on a selection of lakes in the Waikato Region for environmental reporting purposes (Table 1) The Council has used a range of trophic state and biological indicators (Table 2). Sampling is generally carried out three times per year between December and May of each sampling period.

This report was commissioned by the Waikato Regional Council to undertake an external independent review of the programme to date to determine:

1. Whether indicators as used currently are appropriate for the purposes of evaluating lake health and effectiveness of management activities.

2. Whether the frequency of monitoring as currently employed is sufficient for these purposes.

3. Whether additional indicators exist that could/should be investigated.

Specifically, the Waikato Regional Council is seeking clarification on the question of whether monitoring of each lake on three occasions (generally December, March and May) is sufficient to provide a meaningful measure of lake health using the current indicators of Trophic Level Index (TLI, as a measure of lake trophic status), LakeSPI as a measure of status of submerged benthic vegetation and Rotifer TLI as an additional measure of lake trophic status. More specifically, questions arising include:

1. Although limited temporal data are available, are there indicators that show greater sensitivity to detect changes in lake health?

2. Does the state of a lake (e.g. turbid or clear) affect the sensitivity of the indicator?

3. If so, is there sufficient evidence to suggest that sampling frequency could be altered to better align with lake state?

4. Is the sampling frequency and seasonal spread of data collection (December, March and May) appropriate to integrate the relevant environmental stressors experienced within the sampled lakes?

5. Based on any observations in currently and previously monitored lakes, are there lakes that should either remain or be reinstated to the sampling list for 2011/2012 (excluding six lakes which are designated long-term monitoring sites)?

6. What additional variables (e.g., phytoplankton measures and/or biochemical oxygen demand (BOD)) could be used to indicate lake health?

7. What is the best way to interpret the data set and what conclusions can be reached with respect to the ongoing nature of the monitoring programme (e.g. frequency of sampling, cost of adding potential indicators (e.g. phytoplankton and/or BOD).

No judgment of lake health or water quality is made for individual lakes unless the data for the lake help to address one or more of the questions posed above.

For clarity, the seven questions above were categorised into three broader themes:

1. **Adequacy of sampling frequency (**Questions 1, 4 and 5)
2. **Regime shift and/or alternative stable states (**Questions 2 and 3)
3. **Alternative indicators (**Questions 6 and7)

Table 1: Lakes sampled as part of the Waikato Region shallow lakes monitoring program. Sampling duration periods (Dec.-May) are marked for each lake. Asterisk indicates lakes with long term water quality data available.

Lake	Lake type	2006-07	2007-08	2008-09	2009-10	2010-11
Areare	Peat					✓
Hakanoa*	Riverine					✓
Harihari	Aeolian	✓	✓	✓	✓	✓
Kaituna	Peat	✓				
Kimihia	Riverine	✓				
Koromatua	Peat	✓				
Mangahia	Peat	✓	✓	✓	✓	✓
Mangakaware	Riverine					✓
Maratoto*	Peat		✓	✓	✓	
Milicich	n.d.			✓	✓	
Ngahewa	Volcanic		✓	✓	✓	
Ohinewai	Riverine		✓	✓	✓	✓
Okowhao	Riverine		✓	✓	✓	
Otamatearoa	Aeolian	✓		✓	✓	✓
Parangi	Aeolian		✓			
Penewaka	n.d.					✓
Puketi	Aeolian					✓
Rotokawau	Peat		✓			
Rotokotuku	Riverine					✓
Rotomanuka*	Peat		✓	✓	✓	✓
Serpentine East*	Peat		✓	✓	✓	✓
Serpentine North*	Peat	✓	✓	✓	✓	✓
Serpentine South	Peat		✓	✓	✓	✓
Taharoa	Aeolian	✓	✓	✓	✓	✓
Tutaeinanga	Volcanic		✓	✓	✓	
Waahi*	Riverine	✓	✓	✓	✓	✓
Waikare*	Riverine		✓	✓	✓	✓
Whangape*	Riverine		✓	✓	✓	

Table 2: Measured variables for the Waikato Region shallow lakes monitoring program.

Variable	Abbreviation	Unit	Sampling frequency
Temperature	Temp	°C	On each sampling occasion
Dissolved oxygen	DO	mg L^{-1} and % saturation	On each sampling occasion
pH	-	-	On each sampling occasion
Conductivity	Cond	mS m^{-1}	On each sampling occasion
Secchi depth	-	m	On each sampling occasion
Turbidity	Turb	NTU	On each sampling occasion
Total suspended solids	TSS	g m^{-3}	On each sampling occasion
Volatile suspended solids	VSS	g m^{-3}	On each sampling occasion
Ammonium	NH_4-N	g m^{-3}	On each sampling occasion
Nitrate+nitrite	NNN	g m^{-3}	On each sampling occasion
Phosphate	DRP	g m^{-3}	On each sampling occasion
Total Kjeldahl Nitrogen	TKN	g m^{-3}	On each sampling occasion
Total phosphorus	TP	g m^{-3}	On each sampling occasion
Trophic Level Index	TLI	-	Derived (Burns et al., 1999)
Rotifer TLI	-	-	Derived (Duggan et al. 2001)
LakeSPI	-	-	Occasionally
Native condition index	LakeSPIn	-	Occasionally
Invasive condition index	LakSPIi	-	Occasionally
Invertebrate samples	-	No. of taxa	Once (2007-2008)
Wood decomposition	Wood k mean	day^{-1}	Twice (2006-2007 and 2007-2008)

2 Methods

2.1 Adequacy of sampling frequency

The central focus of the shallow lakes indicator program is to develop and test indicators that can be used to infer lake health ('status') and detect changes in water quality/lake health ('trends'). To be able to detect directional changes over time, sampling frequency and duration need to be sufficient to allow detection of changes that exceed a 'background' temporal variability (McBride & Smith, 1997). The current sampling frequency (three times each year) and duration (between one and five years) for the shallow lakes indicator program may be inadequate to accurately quantify temporal variability, specifically trends, in the lakes. The Waikato Regional Council also conducts trophic state monitoring of eight shallow lakes (see Table 1) in the region on a monthly basis with data collected as far back as the early 1990s. It is acknowledged that these eight lakes may not be representative of all the lakes sampled within the shallow lakes indicator program, but they are intended to exemplify the magnitude and range of temporal variability in the shallow lakes. Temporal variability was quantified based on comparisons between years and between different seasons (summer, autumn, winter, spring), and different months (January to December) across different years.

The coefficient of variation (CV) was used to quantify variability of water quality variables collected as part of the long term monitoring of eight lakes (monthly samples). The CV value is defined as CV=standard deviation/mean value. By using this ratio, the CV has no unit and can therefore be used to compare variability of different variables which have different measurement dimensions. Coefficients of variation were calculated for conductivity (Cond), pH, Secchi depth (SD), turbidity (Turb), dissolved reactive phosphorus (DRP), ammonium (NH_4-N), oxidised nitrogen (NNN), total Kjeldahl nitrogen (TKN), total phosphorus (TP), and chlorophyll *a* (chl *a*). The CV values were calculated in three different ways from: (i) annual average values (between 2002-2010) to determine variability between different sampling years, (ii) seasonal average values (i.e. summer, autumn, winter, spring) across several years to determine variability between seasons, (iii) from average values of individual months across several years (e.g. average value of samples collected in January in eight years between 2002 and 2010). Seasons were defined as: Summer (December, January, February), autumn (March, April, May), winter (June, July, August), and spring (September, October, November).

Håkanson (1984) derived a general formula from the basic definitions of the mean value, the standard deviation and the Student's *t*-value. This formula expresses how many samples (N) are required to establish a mean value within a specified certainty: $N=(1.96\times CV/L)^2+1$, where L is the 'level of error' in the mean value. Generally, the number of samples (N) and the CV value are known for a given variable, so that the sampling formula can be solved for L which can be interpreted as a percentage of the mean value. For example, L=0.2 implies 20% error so that the measured mean value will be expected to lie within 20% of the true mean value with the probability assumed in determining the Student's *t*-value. For the purpose of this review, the desired accuracy of the mean value was assumed to be at ≥95% certainty (i.e. $p\geq0.05$), and accordingly a corresponding *t*-value of 1.96 was used.

To assess whether the sampling frequency and seasonal spread of data collection are sufficient to determine the state within the sampled lakes, probability distributions were produced. For this analysis, only the long term records based on monthly sampling for eight lakes were used. Probability distributions were calculated of:

1. The ratio of summer mean/annual mean. Summer mean values were calculated for the months December, January, February in a given year and annual mean values were calculated for 12 months in a given year. Assumption: If the

summer period is the most stressful annual condition, then this ratio is >1 for nutrient and chl *a* concentrations and <1 for SD.

2. The ratio of summer mean/seasonal mean. Assumption: If the summer period is the most stressful period across all seasons, then this ratio is >1 for nutrient and chl *a* concentrations and <1 for SD.

3. The ratio of six-months mean (i.e. December to May)/seasonal mean (i.e. June to November). Assumption: If the six-month period December to May is the most stressful one within the annual period, then this ratio is >1 for nutrient and chl *a* concentrations and <1 for SD.

To test whether there is redundancy in measuring both the TLI value (Burns et al., 1999) and the Rotifer TLI (Duggan et al., 2001) these indicators were compared using linear regression analysis. For this analysis, data were taken from 28 lakes currently in the shallow lakes indicator program (Table 1), spanning sampling periods between 2006 and 2011.

2.2 Regime shift and/or alternative stable states

Regime shifts in the Waikato lakes are generally poorly documented. Whilst some lakes have a comprehensive macrophyte data set available for multiple years, others do not. Scheffer and Carpenter (2003) proposed three lines of evidence for demonstrating alternative stable regimes in ecosystems from field data.

- **Jumps in time series data**

  Sudden changes in time series of trophic state or clarity indicators can be indicative of regime shifts. However, shifts between ecological regimes can be sudden or show a long period of transition, making it difficult to assess the existence of alternative states when limited time series data are available. The ability to resolve regime shifts in shallow lakes with traditional indicators (e.g. turbidity, nutrients; Scheffer et al., 1993) is relatively coarse in the Waikato shallow lakes indicator program due to low frequency of measurements. The long-term data set of eight shallow lakes have either inadequate temporal resolution of macrophyte data or had macrophyte data for multiple years which showed little change in LakeSPI scores. Therefore, time series analysis was not considered further in this study.

- **Multimodality of the frequency distribution of states**

  The frequency distribution of key in-lake variables should show multimodality in lakes which have undergone regime shifts. Statistical tests for multimodality require large datasets. They generally show poor predictive power for limited datasets, which increases the chance of detecting unimodal distributions when in fact the data are multimodal. The analysis of frequency distributions for multimodality was not considered further in this study.

- **Dual relationship to control factors**

  It is important to understand the relationship between the response variable of a lake (e.g. chl *a*, turbidity) to external control factors (e.g. nutrient loading). When the response variable to an external control factor can be described best by two separate regression functions rather than a single function, the external factor can be interpreted as a moderating factor on the relationship.

For the purpose of this study, chl *a* - nutrient relationships were analysed using least-square linear regression analysis on log transformed chl *a*. TP and total nitrogen (TN=NNN+TKN) concentrations for data collected in 28 shallow lakes over the period 2006 until 2011. Data were categorised into non-vegetated and vegetated lakes using the most recent macrophyte survey data based on Edwards et al. (2009). Lakes with a LakeSPI score of zero were categorised as ‘non-vegetated’, and lakes with a LakeSPI

score of >0 were categorised as 'vegetated'. Where there were ≥two macrophyte surveys in a given lake in the period 2006-2011 it is possible to obtain both. For example, Lake Serpentine South had LakeSPI scores >0 for the years 2001 and 2008 but a score of 0 for the year 2009. Analysis of covariance (ANCOVA) was used to test for significant differences of the regression lines between the two vegetation categories. The vegetation category was interpreted to moderate the chl *a* - nutrient relationship if the interaction term was significant. Prior to analysis, data were log transformed to meet assumptions of normality and homogeneity of variance. ANCOVA was carried out in Statistica v. 8.0 (StatSoft Inc.).

A graphical approach to the basic idea of alternative stable states in shallow lakes (i.e. turbidity as a function of nutrients) was used to determine if turbidity and/or TP could be used to predict the presence and absence of aquatic vegetation (Scheffer et al., 1993). Measurements of in-lake TSS and TP were plotted as a bi-scatter plot, using data collected from 28 shallow lakes over the period 2006 until 2011.

Additionally, a Principal Component Analysis (PCA) was carried out with Primer v. 6.1.13 (Primer-E Ltd.) to graphically illustrate how vegetated and non-vegetated lakes were arranged along in-lake chemical and biological gradients. For this analysis, 14 variables from 28 shallow lakes collected between 2006 and 2011 were used. Data were scaled to have zero mean and unit variance prior to analysis. The non-parametric Mann–Whitney U test was used on 14 variables to test whether non-vegetated lakes tended to have larger values than vegetated lakes. The Mann–Whitney U test was carried out in Statistica v. 8.0 (StatSoft Inc.).

2.3 Alternative indicators

A literature review was carried out to summarise two alternative indicators which could potentially be added to the Waikato shallow lakes indicator program. The focus was on biochemical oxygen demand and phytoplankton, two components which are regularly included in other lake monitoring programs but have received little attention in the Waikato shallow lakes' indicator project.

3 Results

3.1 Adequacy of sampling frequency

3.1.1 Variability of water quality variables across different temporal scales

Figures 1, 2 and 3 show a compilation of annual, seasonal and monthly CV values from surface samples. Generally, CV values were highest for NH_4-N and NNN and lowest for pH and DRP. There were major differences in CV values for any of the given variables if the average was calculated over an annual, seasonal or monthly time scale. Naturally, annual CV values were often higher than seasonal and/or monthly CV values because mean values were calculated over a longer time period incorporating different seasons. There were major differences in annual CV values between different years (i.e. the range of annual CV values within a given lake). For example, the annual CV value for TKN in Lake Whangape was calculated to be as low as 0.049 for the period 2003-2004 and as high as 1.04 for 2004-2005 (see Appendix II). There were also differences between seasonal CV values. For example, CV values for NH_4-N in Lake Waikare were as low as 0.58 in spring and as high as 2.16 in summer (see Appendix III). Variability across seasons was also confirmed by differences in monthly CV values. For example, CV values for NNN in Lake Rotomanuka were as low as 0.41 in September and as high as 1.89 in December (see Appendix IV).

It is important to note that in all lakes the variability for most variables was very high and resulted in a large error in the mean value (Figure 4). If the CV value was 1.0, for example, then 97 samples would be required to determine the mean value with an

error < 20%. Given the inherent variability of all water quality variables based on the long-term data set, for which samples had been collected mostly at a monthly interval, it is questionable if sampling frequency in the current monitoring program should be reduced at all. A mock example of reducing the number of samples from 12 per year to 3 per year is shown in Figure 4. The CV value for chl *a* in Lake Maratoto for the period 2007-2008 was 0.25 based on monthly (N=12) samples. By reducing the number of samples to three, which is currently the sampling frequency of the shallow lake indicator program, the error in the mean value would increase to 0.55. This exercise can be carried out for any variable and it becomes clear that for variables with a characteristically high CV value of >1.5 (e.g. NNN) in these shallow lakes, the number of samples required to determine the mean value with a desired accuracy would be very large.

Errors in the mean value of variables with a characteristically high CV value can only be reduced by a higher number of samples. For example, a lake monitoring buoy in Lake Ngaroto was deployed in July 2008. This buoy is recording data for several different variables including chlorophyll and turbidity at a 15 minute interval (Chris McBride, University of Waikato, pers. comm.). Calculated CV values for chorophyll and turbidity recorded between July 2009 and June 2010 were 0.52 and 0.42, respectively. Given the large number of data points recorded during this period (14812 for chlorophyll, 31311 for turbidity), the resulting errors in the mean value L, were very small (0.0085 for chlorophyll, 0.0146 for turbidity). Temperature data recorded by the lake buoy thermistor chain show that Lake Ngaroto, despite its relatively shallow maximum depth of 4 m, stratifies during summer for periods of up to several days. During some of these stratification events, dissolved oxygen concentrations in the bottom waters approach 0 mg L^{-1}. These anoxic events can potentially have a significant impact on the overall lake dynamics with regards to nutrient cycling and phytoplankton growth, but are likely to be missed during monitoring at time scales currently carried out for other Waikato shallow lakes. While the inclusion of organisms, such as Rotifers, into the monitoring program may better reflect long term conditions in a given lake (i.e. invertebrates integrate time better than ‘spot’ sampling of the water column), the time scales of response of these organisms remains unclear.

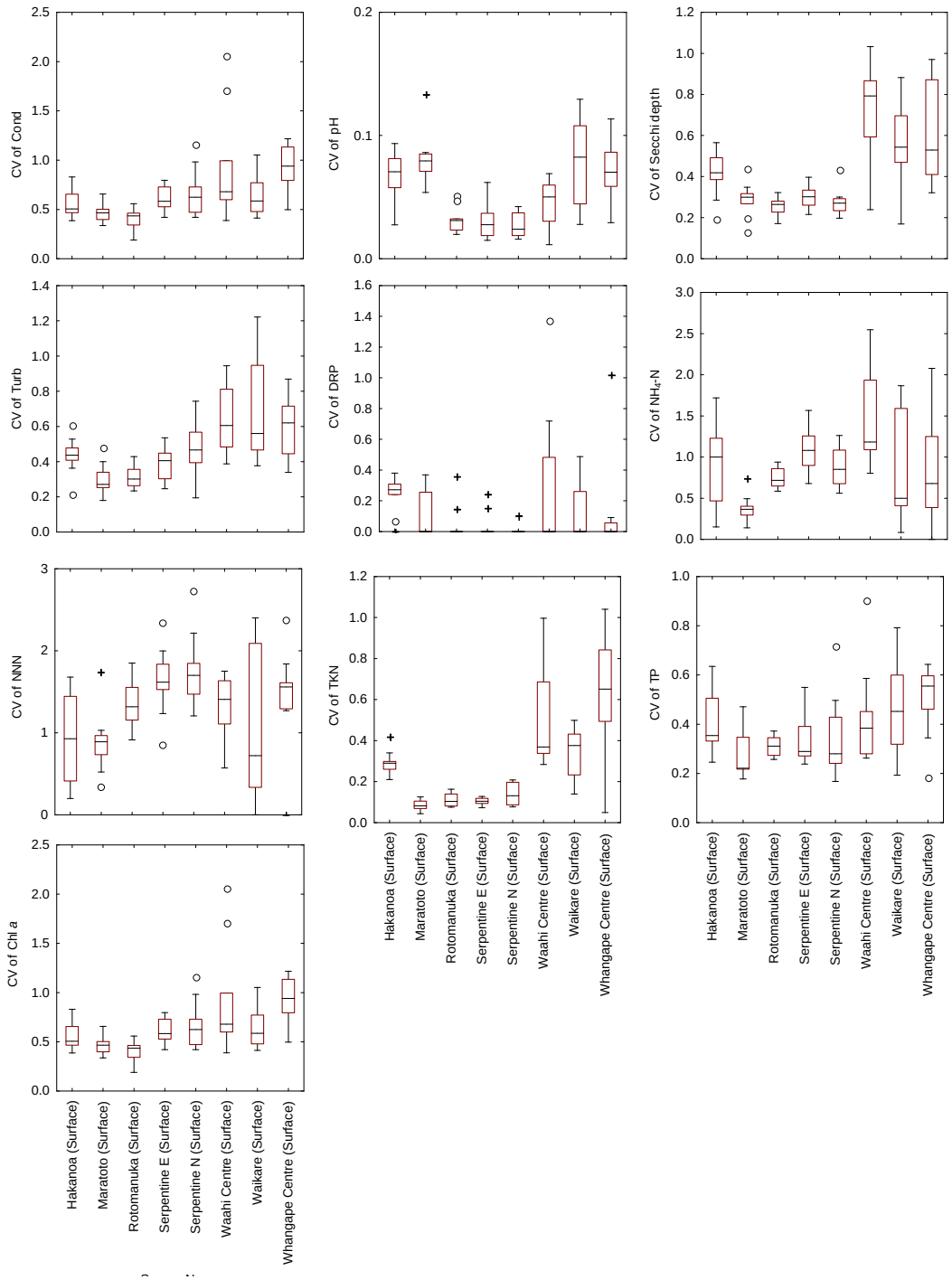


Figure 1: Compilation of median annual CV values for different water quality variables based on data from surface measurements, 2002-2008, for eight Waikato lakes. Annual CV values were calculated from annual average values between 2002 and 2010. Lines represent the median value, boxes represent 25% and 75% percentiles, whiskers represent the non-outlier range, circles represent outliers and asterisks represent extreme values. (Bottom water samples are shown in Appendix V.)

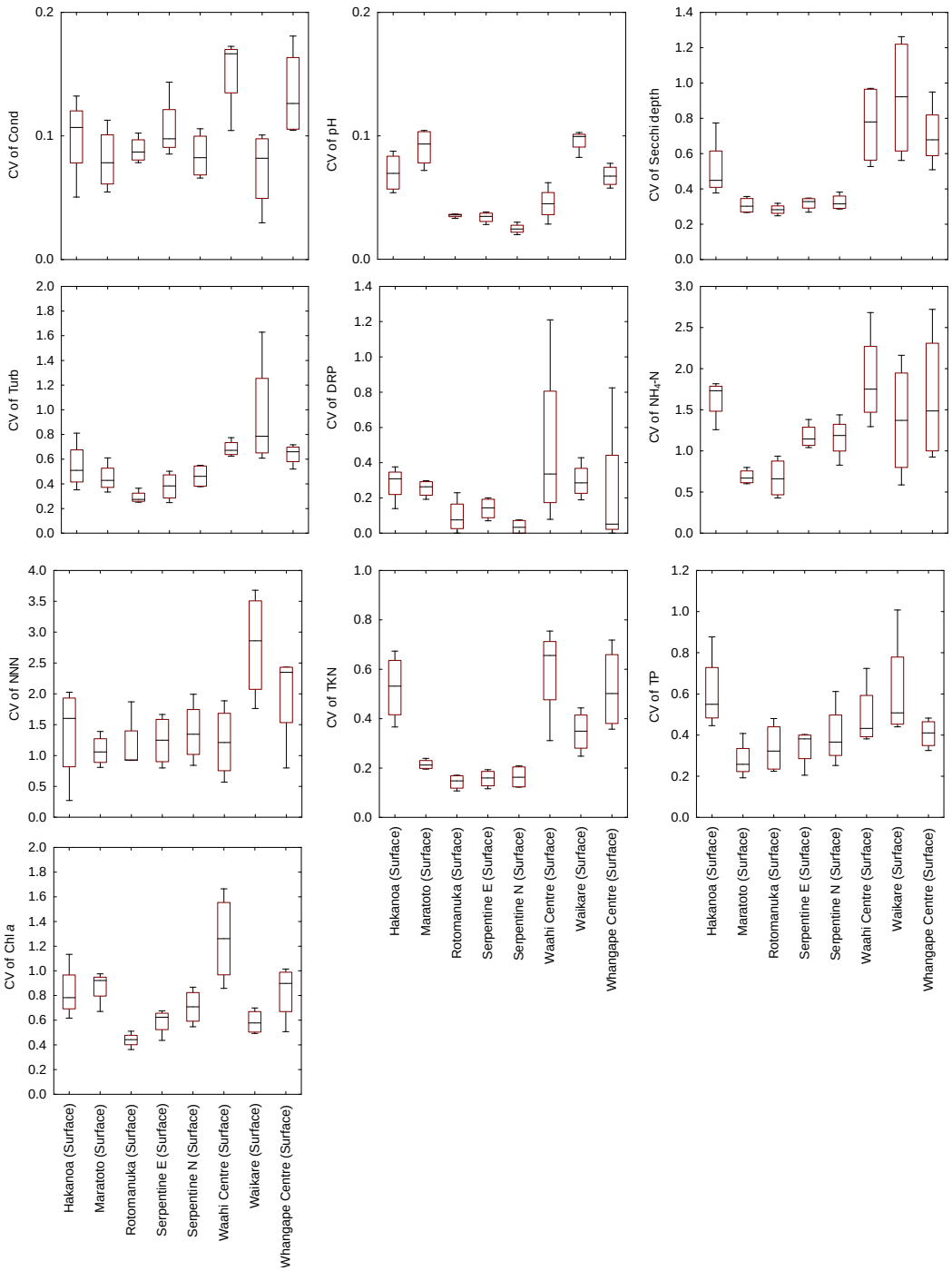


Figure 2: Compilation of median seasonal CV values for different water quality variables based on data from surface measurements between 2002-2008 for eight Waikato lakes. Seasonal CV values were calculated from seasonal average values (i.e. summer, autumn, winter, spring) across several years. Lines represent the median value, boxes represent 25% and 75% percentile, whiskers represent the non-outlier range, circles represent outliers and asterisks represent extreme values (Bottom water samples are shown in Appendix V).

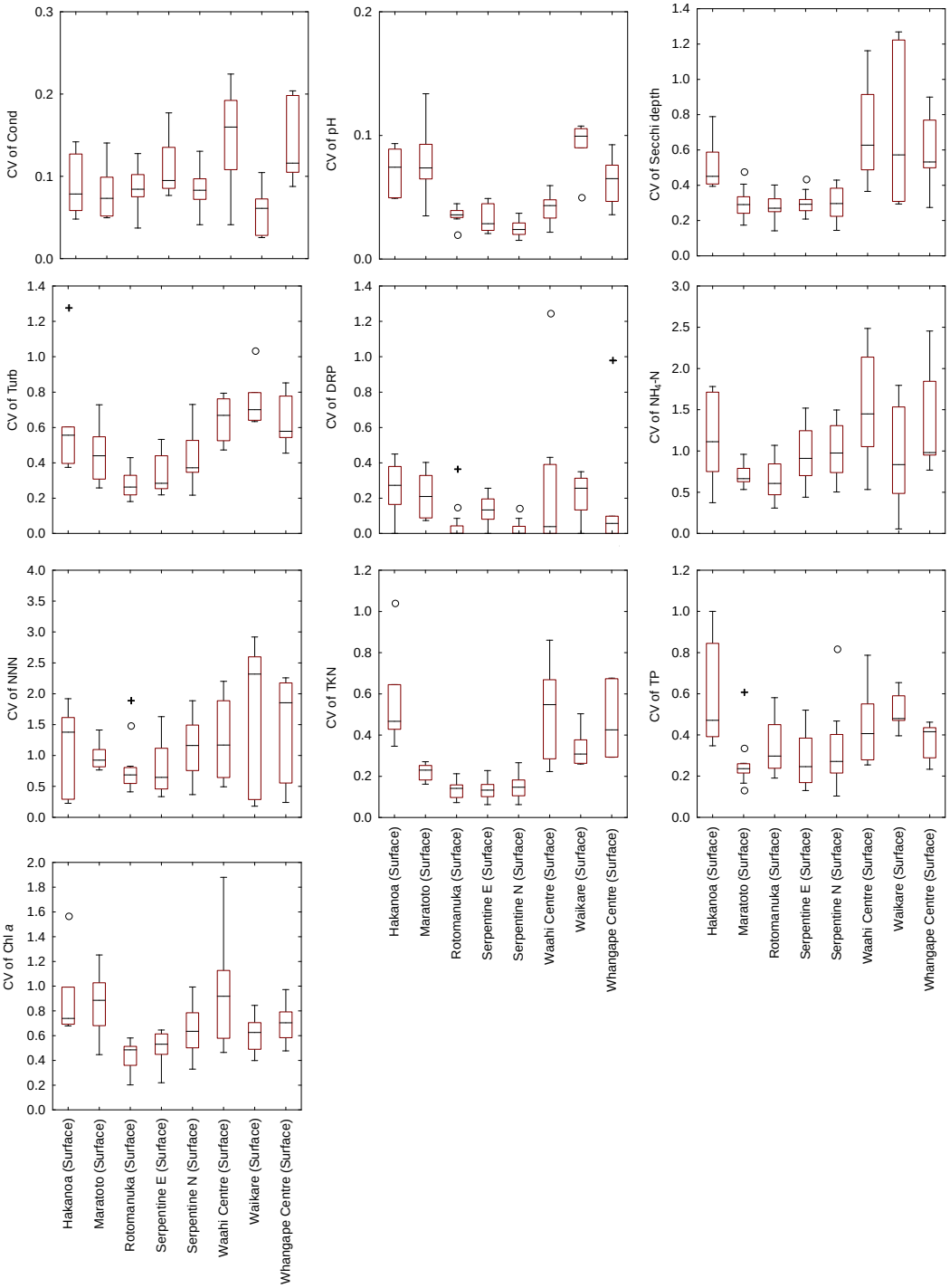


Figure 3: Compilation of median monthly CV values for different water quality variables based on data from surface measurements between 2002-2008 for eight Waikato lakes. Monthly CV values were calculated from monthly average values (i.e. January until December) across several years. Lines represent the median value, boxes represent 25% and 75% percentile, whiskers represent the non-outlier range, circles represent outliers and asterisks represent extreme values (Bottom water samples are shown in Appendix V).

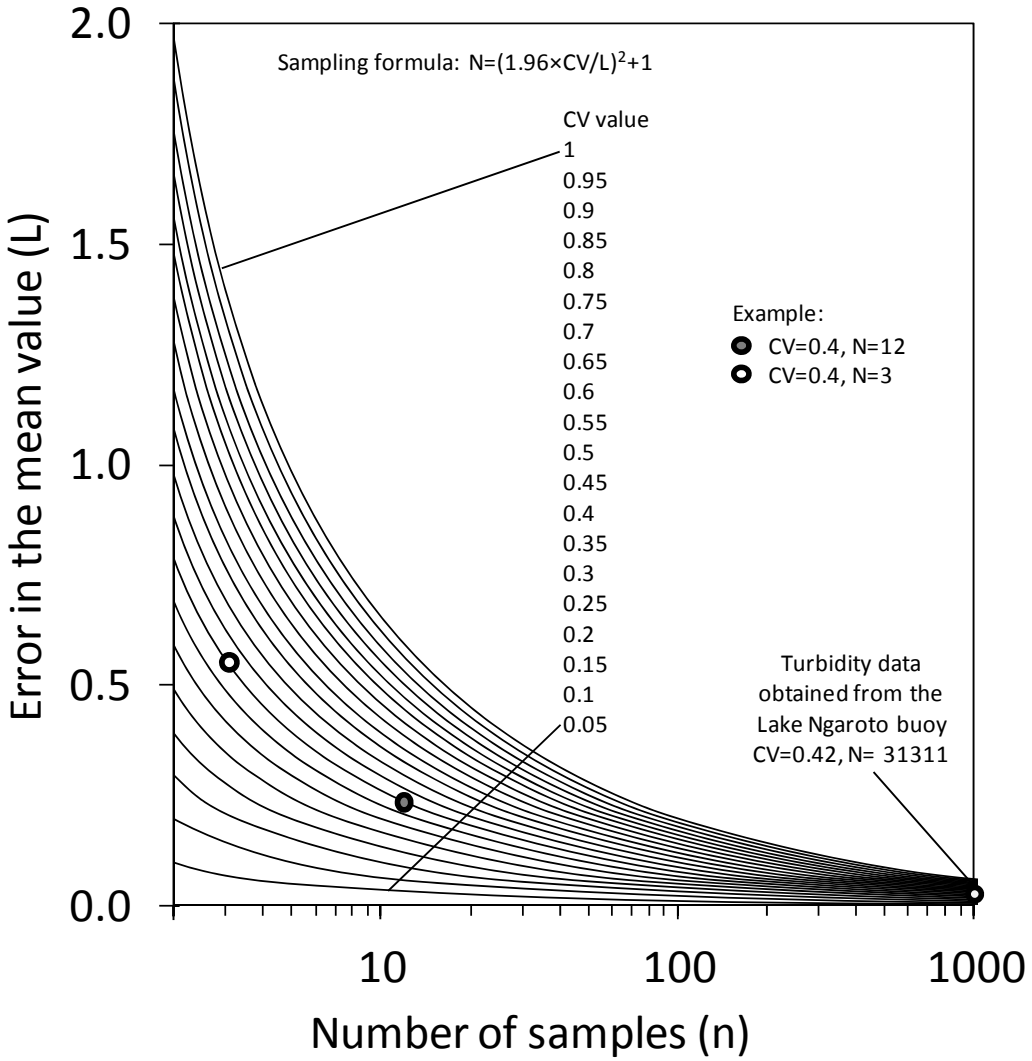


Figure 4: Graphical representation of the sampling formula according to Håkanson, (1984). The example shows the error in the mean value of measured chl *a* concentrations in Lake Maratoto for the year 2007-2008 (0.25) based on monthly sampling and the inferred error in the mean value (0.55) if the number of samples was reduced to three.

3.1.2 Is December, March and May the most stressful period of the year?

To determine whether the period between December and May, which is generally considered to be a growth period for primary producers, is the most stressful in the shallow lakes, frequency histograms were produced of normalised values for summer mean /annual mean, summer mean /seasonal mean and 6-month mean/seasonal mean using long-term records from eight lakes. Seasonal mean values are based on those for spring, autumn and winter. The 6-month period refers to the mean value of monthly samples between December and May (which is currently the sampling regime of the shallow lakes indicator project).

If the ratio of these three normalised values is <1, then the summer mean is smaller than the annual mean or seasonal mean. If the ratio is >1, then the summer mean is larger than the annual mean or seasonal mean. Several values of summer mean/annual mean were <1 (>1 for SD), which indicates that the summer mean may not always represent the most stressful period for these lakes in terms of water quality and primary productivity (Appendix VI). Seasonal means were often substantially higher than the summer mean or 6-month mean (i.e. December to May) values (Appendix figure VI). This was particularly the case for ammonium and nitrate

concentrations, with seasonal mean values up to two orders of magnitude higher than summer mean values.

Cumulative frequency distribution plots were used to show the number of observations ≤1 for the ratio of mean values of summer /annual, summer /seasonal and 6-month (i.e. December to May)/seasonal (Figure 5). Cumulative frequencies were produced of the sum of frequencies across eight individual in-lake measurements for eight lakes. Summer mean values were smaller than seasonal and annual mean values 46% and 52% of the time. The 6-month mean values (i.e. December to May) were lower than the seasonal mean values 48% of the time.

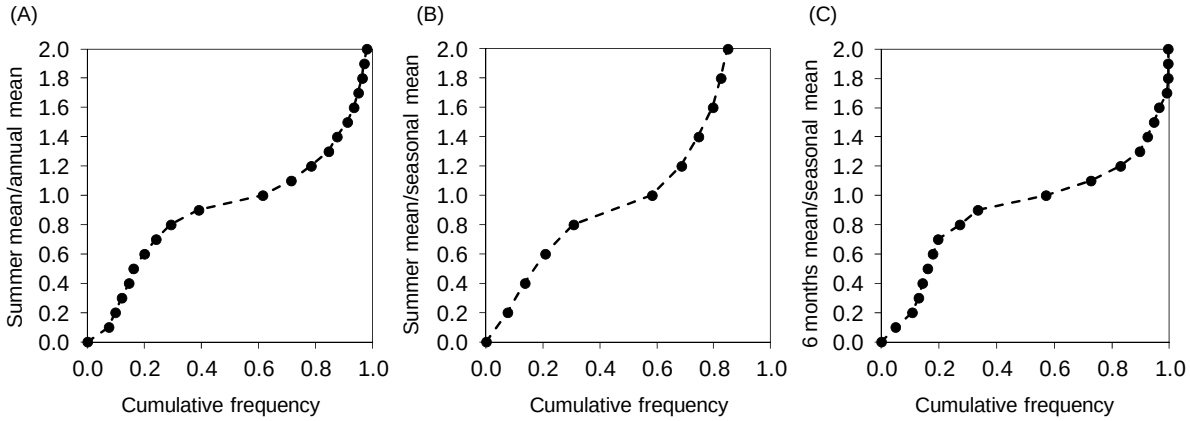


Figure 5: Cumulative frequency distributions of mean values of (A) summer /annual, (B) summer /seasonal and (C) 6-month (i.e. December to May)/seasonal. Cumulative frequencies were produced of the sum of frequencies across eight individual in-lake measurements for eight lakes.

3.1.3 Implications of variability on the ability to detect changes in water quality

Based on the observed variability in the shallow lakes, one must ask if the current sampling frequency is adequate to allow for detection of changes in water quality over time. A number of hypothetical numerical scenarios were used to illustrate the monitoring time scales necessary to detect significant changes in water quality using chl *a* concentrations as an example indicator of water quality. In a base scenario, it was assumed that the measured chl *a* concentrations (±0.5×L) would be constant over time. Changes in water quality were then simulated as dc/dt = b×c, where c is the chl *a* concentrations (±0.5×L) at time t (years) and b is a reduction coefficient. For the reduction scenario, it was assumed that the CV is dependent on magnitude as observed in the long-term data set (Pearson R=0.45, p<0.001 for $CV_{chl\ a}$ vs. mean chl *a*).

Reduction scenarios were set up in two different ways to address the following questions:

a. How long will it take to detect a significant change in water quality for a given lake which has moderately high variability?

b. How severe would a change in water quality need to be to be able to detect a significant change within five years of monitoring a lake with moderately high variability?

To answer question (i), chl *a* concentrations in Lake Maratoto for the period 2007-2008, N=12, CV=0.4, L=0.25) were used. The scenarios included the simulation of mean values of chl *a* and L for the base case and a reduction scenario for a sample size of N=12 per year (L_{t0}=0.25) and for N=3 per year (L_{t0}=0.55). The reduction coefficient b was set at 0.975 (i.e. 2.5% per year), so that after approximately 30 years, the chl *a* concentrations would have been reduced by 50%. A second set of scenarios was simulated using chl *a* concentrations from Lake Hakanoa (mean value from long-term

records based on monthly sampling program) for the period December 2010 until May 2011 (N=6, CV=0.63, L=0.55) which encompasses the sampling period of the indicator monitoring program. This scenario was then compared to the indicator monitoring program (N=3) for the same period (i.e. December 2010-May 2011). To answer question (ii) the reduction coefficient b was altered to determine t=5 years using the same examples than above. Microsoft® Excel Solver was used to optimise b. A significant change in water quality was interpreted to have occurred when the mean values ±0.5×L no longer overlapped.

The model simulations have shown that it will take several years of monitoring before a significant change in water quality can be detected. By taking monthly samples, it could take up to 10 years before a continuous decrease in chl *a* concentrations by 3% yr^{-1} can be determined as statistically significant (Figure 6A). Reducing the number of samples to three per year, the time to detect a change increases to 23 years (Figure 6B). A comparison of the effect of number of samples during the period December 2010 and May 2011 in Lake Hakanoa has shown that it would take up to 23 years for N=6 and 41 years for N=3 before a significant change in water quality would be detected (Figure 6C and D).

To be able to detect any changes in water quality over shorter periods (e.g. 5 years), any reduction of chl *a* concentrations would have to be substantial (Figure 7). Reduction coefficients ranged from 0.78 (Lake Hakanoa, N=3, CV=0.63, L=0.9) to 0.94 (Lake Maratoto, N=12, CV=0.4, L=0.55) (Table 3). These coefficients indicated that chl *a* concentrations would have to be reduced by up to 22% yr^{-1} to be able to detect a significant change in water quality within 5 years of monitoring.

Table 3: Model parameter summary for simulating chl *a* concentrations in lakes Maratoto and Hakanoa to answer question (i) How long will it take to detect a significant change in water quality for a given lake which has moderately high variability? and (ii) How severe would a change in water quality need to be to be able to detect a significant change within five years of monitoring a lake with moderately high variability? (see text for detailed model description).

Lake	Question	N	CV	L	b (yr^{-1})	t (years)
Maratoto	(i)	12	0.4	0.25	0.975	10
	(i)	3	0.4	0.55	0.975	23
	(ii)	12	0.4	0.25	0.94	5
	(ii)	3	0.4	0.55	0.86	5
Hakanoa	(i)	6	0.63	0.55	0.975	23
	(i)	3	0.63	0.9	0.975	41
	(ii)	6	0.63	0.55	0.86	5
	(ii)	3	0.63	0.9	0.78	5

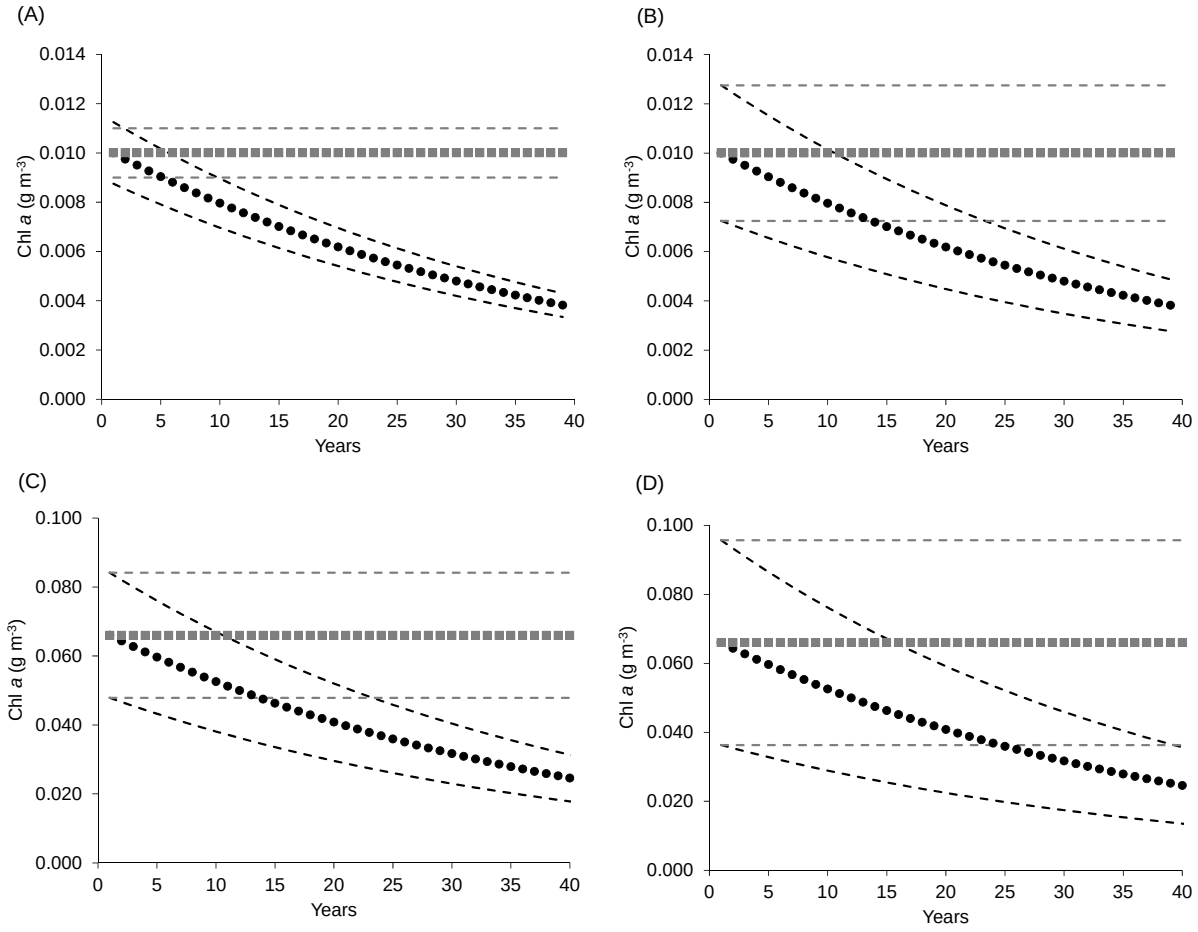


Figure 6: (A) Simulated chl *a* concentrations (±0.5×L) for the base case and reduction scenarios (b=0.975) in Lake Maratoto for monthly sampling, (B) simulated chl *a* concentrations (±0.5×L) for the base case and reduction scenarios (b=0.975) in Lake Maratoto for three samples per year, (C) simulated chl *a* concentrations (±0.5×L) for the base case and reduction scenarios (b=0.975) in Lake Hakanoa for six samples between December 2010 and May 2011, (D) simulated chl *a* concentrations (±0.5×L) for the base case and reduction scenarios (b=0.975) in Lake Hakanoa for three samples between December 2010 and May 2011.

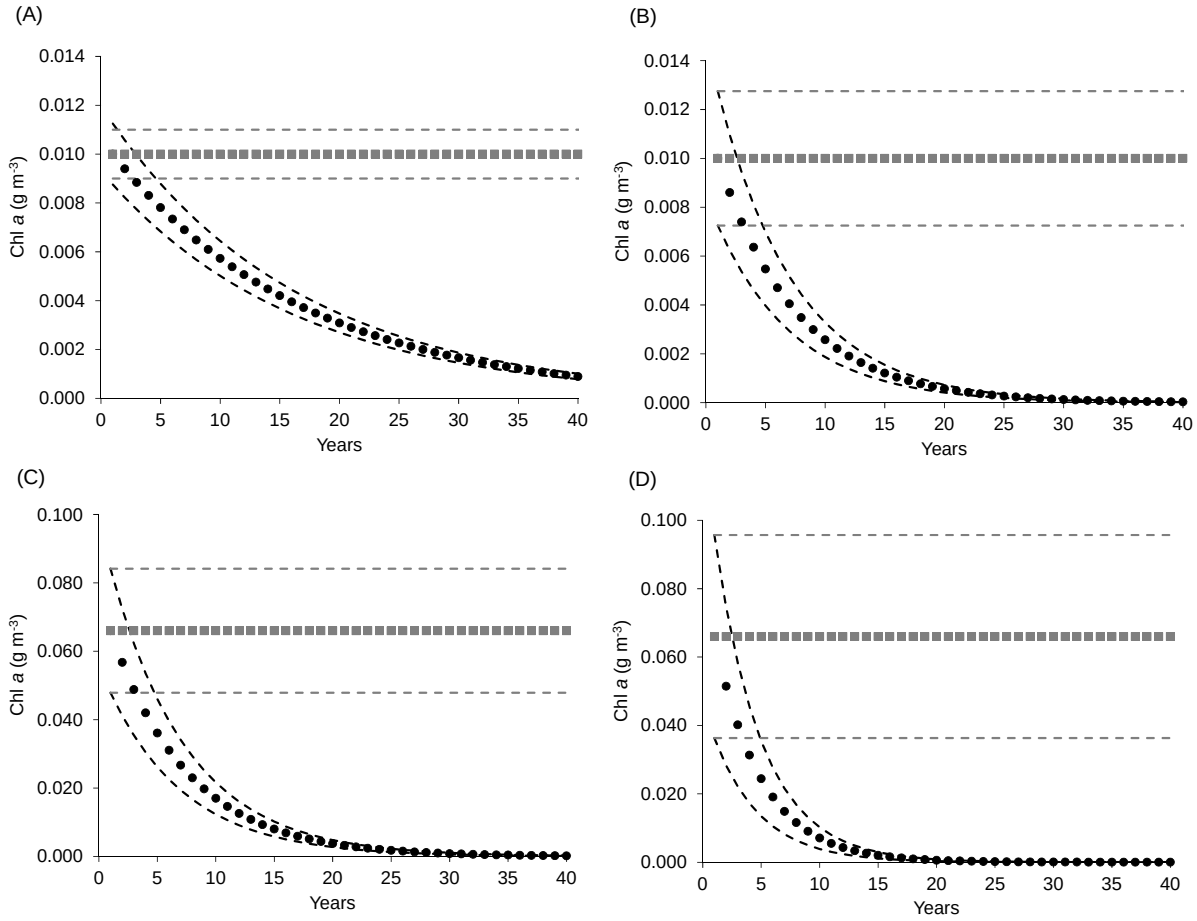


Figure 7: (A) Simulated chl *a* concentrations (±0.5×L) for the base case and reduction scenarios in Lake Maratoto for monthly sampling, (B) simulated chl *a* concentrations (±0.5×L) for the base case and reduction scenarios in Lake Maratoto for three samples per year, (C) simulated chl *a* concentrations (±0.5×L) for the base case and reduction scenarios in Lake Hakanoa for six samples between December 2010 and May 2011, (D) simulated chl *a* concentrations (±0.5×L) for the base case and reduction scenarios in Lake Hakanoa for three samples between December 2010 and May 2011. The reduction coefficient b was optimised to be able to detect a significant change in water quality within 5 years of monitoring.

3.1.4 Comparison of TLI vs. Rotifer TLI

The comparison of TLI and Rotifer TLI shows that the Rotifer TLI explains 62.4% of the variation in the TLI values (Figure 8). At lower Rotifer TLI values (i.e. < 3), the TLI appears to be predicted poorly. The majority of TLI values could potentially be predicted within ±0.5 TLI units, but 10 out of 61 TLI values were predicted poorly (i.e. ± >0.5 TLI units) with discrepancies of up to 2 TLI units (Figure 8). There was no clear indication that the predictive power of Rotifer TLI was influenced by lake type (i.e. categorised by geological formation). It is worth pointing out, however, that there was little variation in TLI values for dune lakes (3.3-5.8) but the Rotifer TLI, ranged from 1.3 to 5.7.

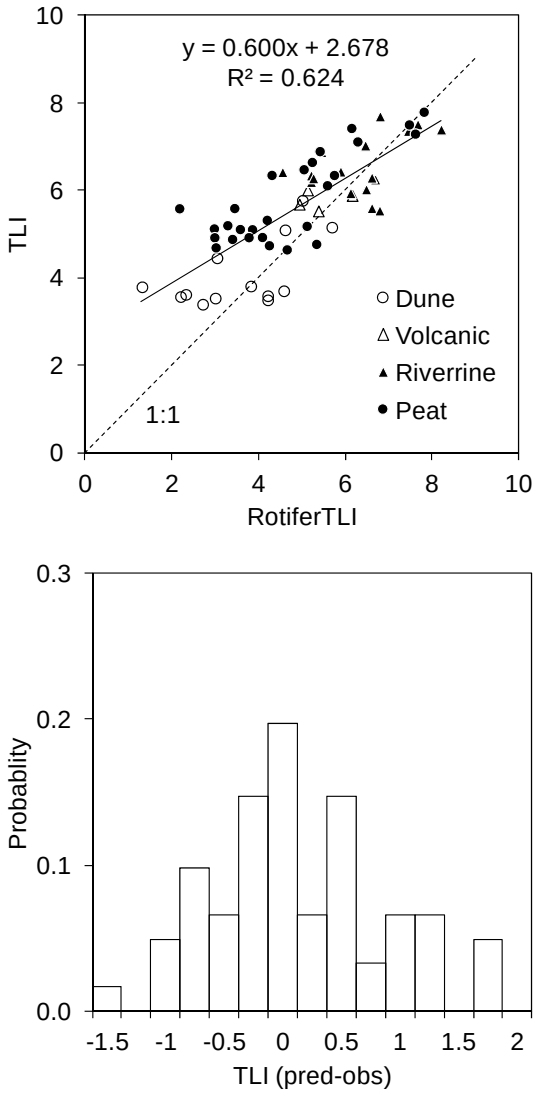


Figure 8: Comparison between Rotifer TLI and TLI based on samples collected from 28 lakes between 2006 and 2010 (dashed line represents 1:1 relationship) and probability distribution of regression residuals (i.e. predicted-observed TLI values) based on the regression equation.

3.2 Regime shift and/or alternative stable states

3.2.1 Signs of regime shift and/or alternative stable states in the Waikato shallow lakes

Figure 9 shows that TP and TN concentrations explain a large amount of the variation in chl *a* concentration in 28 shallow Waikato lakes and these relationships were highly significant ($p<0.01$). Total phosphorus was a better predictor of chl *a* (non-vegetated lakes, $R^2=0.683$; vegetated lakes, $R^2=0.808$) than TN (non vegetated lakes, $R^2=0.754$; vegetated lakes, $R^2=0.393$). Vegetation categories moderate the relationship between chl *a* and TP (ANCOVA, $F=5.95$, $p=0.017$), but not between chl *a* and TN (ANCOVA, $F=0.96$, $p=0.330$). The moderating factor indicates the potential for a dual relationship in the Waikato shallow lakes and suggests that at any given TP concentration, a lake may exhibit different chl *a* responses.

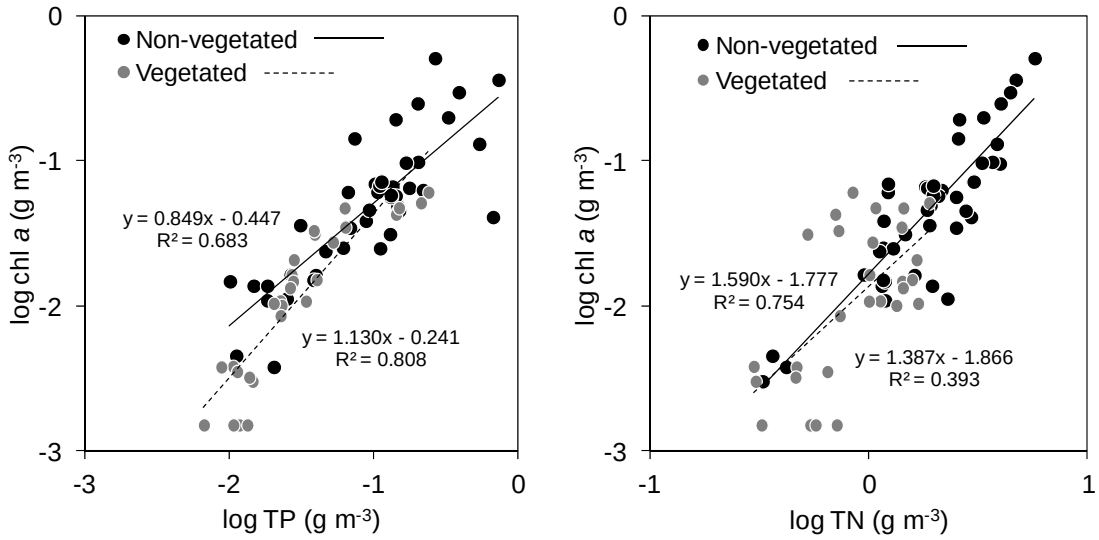


Figure 9: Scatter plots of chl *a* concentration against TP and TN concentrations for 28 shallow Waikato lakes from data collected between 2006 and 2011. Data are log10 transformed and all regressions are significant (p < 0.01).

Figure 10A illustrates a graphical approach to the basic idea of alternative stable states in shallow lakes (i.e. turbidity as a function of nutrients). This model is based on three assumptions (Scheffer et al., 1993): (i) turbidity of the water increases with nutrient level, (ii) macrophytes reduce turbidity and (iii) macrophytes disappear when a critical turbidity is exceeded. Figure 10B shows a scatter plot of field data between TSS and TP concentrations in 28 shallow Waikato lakes. The lakes have been categorised into two different groups, vegetated lakes and other non-vegetated lakes, respectively. It is apparent that the relationship between turbidity and total phosphorus concentrations in these 28 lakes appears to conform to the graphical model of alternative stable states. It is worth pointing out however, that the scatter plot in Figure 10B is based on a multi-lake comparison and not a long-term time series of individual lakes. Therefore, the scatter plot observations should be interpreted with caution, but they highlight that the Waikato shallow lakes may show signs of alternative stable states.

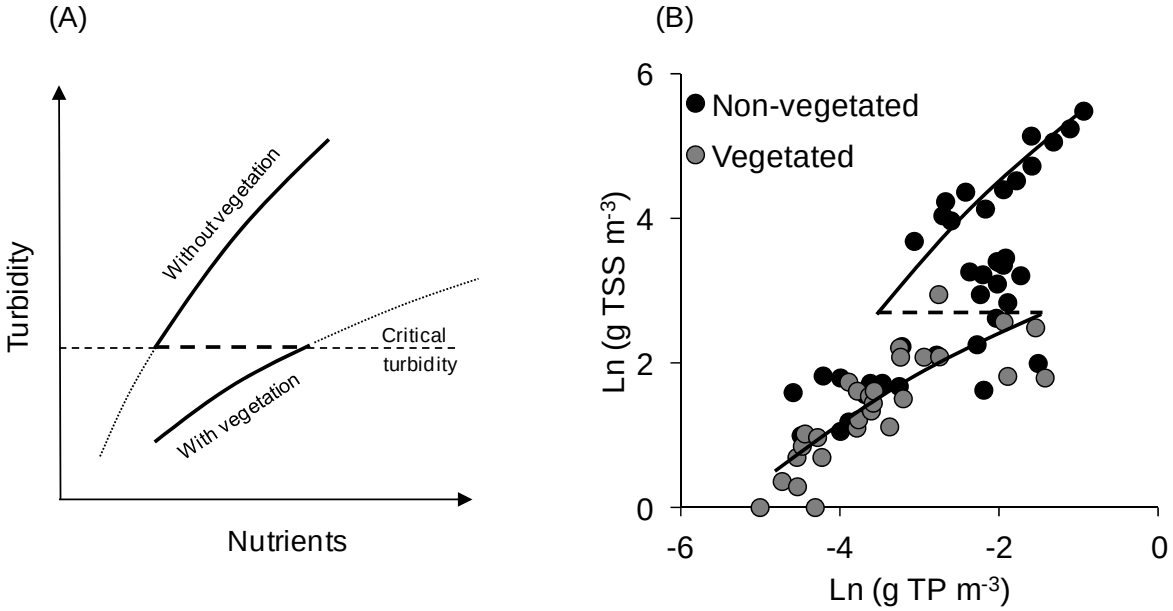


Figure 10: (A) Relationship between nutrients and turbidity in lakes when dominated by phytoplankton (i.e. without 'vegetation curve') or submerged marcrophytes (i.e. 'with vegetation' curve) with the assumption that submerged vegetation completely disappears at a critical turbidity threshold (redrawn from Scheffer et al., 1993) and (B) relationship between TP and TSS in 28 shallow lakes for data collected between 2006 and 2011, with categorisation into vegetated lakes and non-vegetated lakes. The lines through the data in (B) were drawn by eye.

A PCA ordination plot can be used to illustrate how vegetated and non-vegetated lakes are arranged along chemical and biological gradients (Figure 11). There is some overlap between these two categories on the first two principal component axes, suggesting heterogeneity in in-lake conditions within each category. Principal component axis one (PC1) accounts for 47.4% of the total variance in the data and represents a nutrient-clarity-chlorophyll *a* gradient, whereas Principal Component axis two (PC2) accounts for 22.1% of the total variance in the data and represents ion-acidity-alkalinity (conductivity, pH and dissolved inorganic nutrient) gradient. Vegetated lakes tend to have higher clarity and lower turbidity and nutrient concentrations than non-vegetated lakes. Results from a Mann–Whitney U test of in-lake measurements between vegetated and non-vegetated lakes show that turbidity, water clarity, chl *a* and total nutrient concentrations are significantly higher in non-vegetated lakes than vegetated lakes (Table 4).

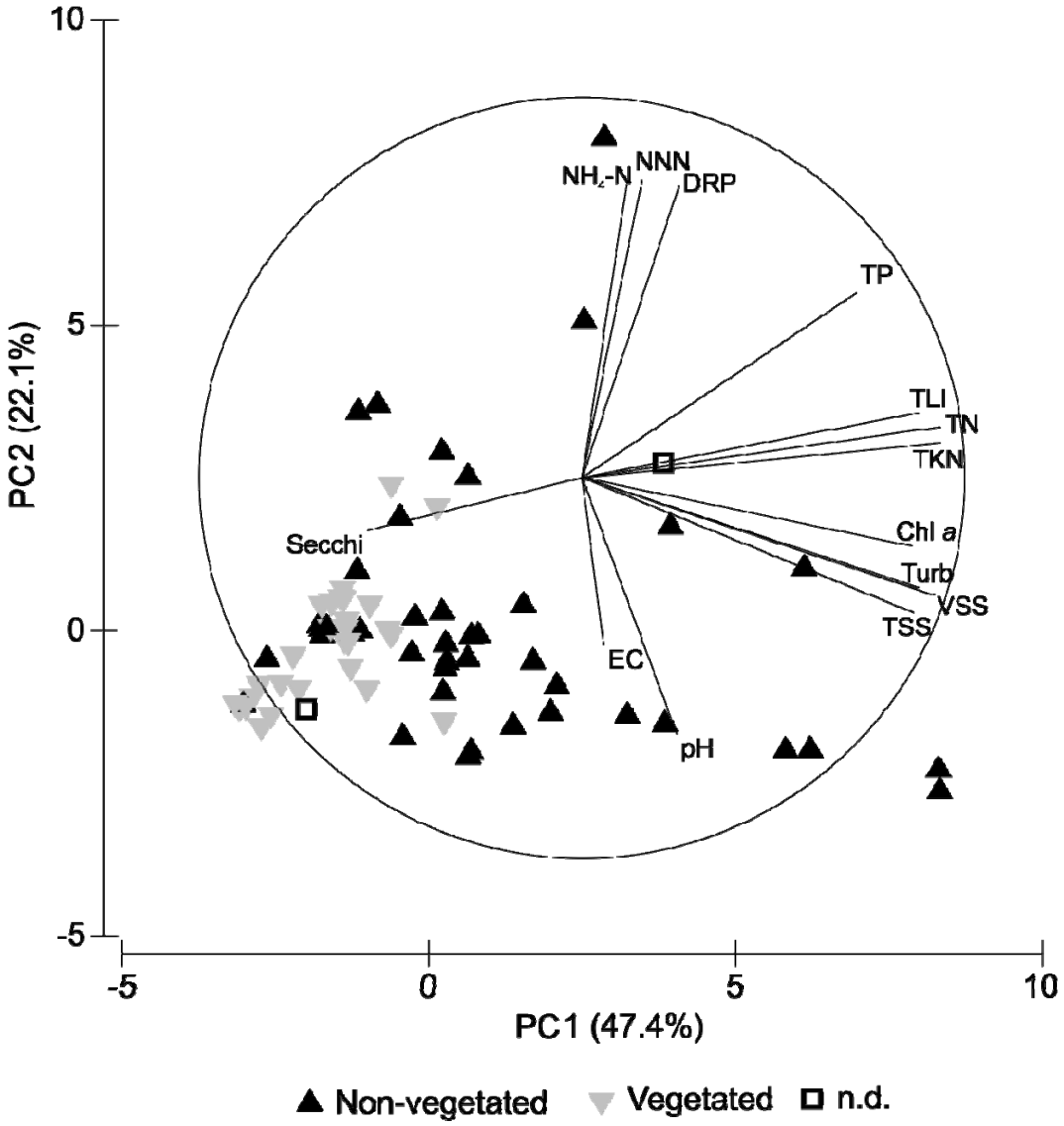


Figure 11: Principal Component Analysis ordination for 28 vegetated and non-vegetated lakes in total in the Waikato Region sampled during the 2006 and 2011(see Table 1) shallow lake indicator project. In-lake measurements of 14 variables are shown overlaying the plot. The first two components accounted for 69.5% of the total variance in the data. Note: n.d. = no macrophyte survey data available.

Table 4: Summary of statistical output of a Mann–Whitney U test of the difference in median values of variables for different trophic state variables between non-vegetated and vegetated lakes (p-values are significant at p<0.05).

Variable	Rank Sum (Non-vegetated)	Rank Sum (Vegetated)	U	Z	p-value	N (Non-vegetated)	N (Vegetated)
Turbidity (NTU)	1982	574	168	5.100	<0.05	43	28
pH	1592	965	559	0.506	0.613	43	28
EC (µS cm^{-1})	1595	962	556	0.541	0.588	43	28
VSS (g m^{-3})	1961	596	190	4.847	<0.05	43	28
TSS (g m^{-3})	1994	562	156	5.242	<0.05	43	28
NH_4-N (g m^{-3})	1645	841	463	1.418	0.156	43	27
NNN (g m^{-3})	1660	896	490	1.312	0.190	43	28
TKN (g m^{-3})	1987	569	163	5.159	<0.05	43	28
DRP (g m^{-3})	1658	898	492	1.288	0.198	43	28
TP (g m^{-3})	1875	681	275	3.841	<0.05	43	28
TN (g m^{-3})	1985	571	165	5.136	<0.05	43	28
Chl *a* (g m^{-3})	1924	633	227	4.412	<0.05	43	28
Secchi depth (m)	1308	1248	362	-2.818	<0.05	43	28
TLI	1896	660	254	4.089	<0.05	43	28

3.3 Alternative indicators

3.3.1 Hypolimnetic oxygen demand

The dissolved oxygen concentration in lakes has been considered to be the single-most important lake monitoring indicator and can reveal more about a lake's metabolism than any other measurement (Hutchison, 1957; Kalff, 2003). Low oxygen concentrations can have detrimental effects on aquatic biota, such as fish and macroinvertebrates (Kolar & Rahel, 1993) and also have a major influence on the solubility of metal cations and associated phosphorus sorption, as well as other inorganic nutrients such as ammonium (Beutel, 2001; Søndergaard, et al., 2003). During stratification, the oxygen consumption, or hypolimnetic oxygen demand (HOD), is made up of two major components: (i) the oxygen demand in the water of the hypolimnion through respiration and (ii) the sediment oxygen demand (SOD) at the sediment-water interface where oxygen is largely consumed through mineralisation of particulate and dissolved organic matter by a number of microbiological pathways.

The HOD has been linked directly to the production of organic matter in the water column (Gelda et al., 1995) and, therefore, to trophic state variables, such as nutrients and chlorophyll *a* concentrations (Burns, 1995). Determining HOD rates in stratified lakes can potentially integrate water column and sediment processes which occur between sampling dates, unlike nutrient concentrations, which can be highly influenced by short-term events preceding the sampling date, such as low nutrient concentrations as a result of an algal bloom which subsequently settles out (Burns, 1995).

The determination of HOD rates can be carried out *in situ* or *in vitro*. For *in situ* determination a time series of vertical profiles of oxygen concentration distribution is needed. For this measurement, the hypolimnion of a lake is assumed to behave relatively independently from the eplimnion, so that, based on a time series of oxygen measurements, the volumetric hypolimnetic oxygen demand (VHOD) can be calculated as:

$$VHOD = \frac{O_t - O_{t+\Delta t}}{\Delta_t}$$

where VHOD is the volumetric hypolimnetic oxygen demand (mg m^{-3} d^{-1}), O_t and $O_{t+\Delta t}$ are the oxygen concentrations at time t and t+Δt, respectively. Morphometry and hypolimnion thickness have been found to influence VHOD values, because a thicker hypolimnion could potentially dilute the sedimenting organic matter and oxygen depletion compared to the same amount of organic matter in a thinner hypolimnion, making multi-lake comparisons difficult. The development of an oxygen depletion rate for a given area of hypolimnetic surface has led to the calculation of the areal hypolimnetic oxygen demand (AHOD) and can be determined by:

$$AHOD = \frac{O_t - O_{t+\Delta t}}{\Delta_t} \times H_h$$

where AHOD is the areal hypolimnetic oxygen demand (mg m^{-2} d^{-1}) and H_h is the mean thickness of the hypolimnion during stratification. It becomes apparent from this calculation that a series of temperature measurements are needed during stratification to accurately determine H_h. The calculations of either VHOD or AHOD do not, however, not distinguish between the oxygen consumption in the water and in the sediments but have been found to correlate well with the trophic state of lakes, so that direct relationships with, for example, water column TP concentrations can be inferred (Chapra & Canale, 1991). Capturing stratification events in some of the Waikato lakes can be difficult as stratification events may occur for short periods of time only and delineation of hypolimnetic dimensions may be difficult due to subtle temperature gradients.

In vitro measurements can be carried out with sediment incubation chambers using intact sediment cores (Gelda et al., 1995) or using biochemical oxygen demand (BOD) assays (Ostapenia et al., 2009). Measurements of BOD can be used to provide valuable information for quantifying rates of breakdown of the organic carbon pools in the water (Ostapenia et al., 2009). By using filtered and/or unfiltered samples these breakdown rates can further be used for partitioning dissolved and particulate carbon pools.

3.3.2 Phytoplankton as biological indicators for lake health

Because of its light-emitting properties, which are shared by all primary producers, chlorophyll *a* concentration is the most widely used proxy for phytoplankton biomass. Knowing phytoplankton species composition, however, can significantly contribute to understanding of the status of lake ecosystems. The concept of using phytoplankton species composition as a biological indicator of water quality is not new and has been used for several decades in lakes across the world (Villegas and DeGiner, 1973; Padisák et al., 2006; Pacheco et al., 2010). Phytoplankton composition can depend on changes in physical (e.g. temperature, light, nutrient concentrations) and biological variables (e.g. grazing pressure by zooplankton, competition between phytoplankton species). The response of phytoplankton composition to these environmental variables can be analysed at different taxonomic levels (e.g. Pacheco et al., 2010) or using function groups (e.g. Padisák et al., 2006). A recent study on the relationship between catchment land use and trophic status impacts on phytoplankton composition in the Rotorua lakes has shown that phytoplankton populations categorised to phyla level can be linked to intensification of land use, and thus nutrient loading (Paul et al.,

submitted). There are also substantial changes in the composition of phytoplankton populations seasonally (e.g. Ryan et al, 2006) and these need to be considered if phytoplankton composition is included in the Waikato shallow lakes monitoring program. However, from Hamilton et al. (2010), there is some evidence of increases in both phytoplankton biomass and relative abundance of cyanobacteria in several of the Waikato lakes. Knowledge of the abundance of phytoplankton species can also help in understanding the dynamics of higher organisms such as zooplankton as the dominance of buoyant toxic cyanobacteria can influence rotifer abundance (Starkweather & Kellar, 1987).

It is recommended that phytoplankton sampling be carried out for the Waikato shallow lakes indicator program to determine changes in phytoplankton species composition within specific lakes and also across lakes. There is scope to develop a phytoplankton indicator for the Waikato shallow lakes which could ultimately be used in an integrated approach to assess lake health. Initially the indicator development will be exploratory but it may allow for resolving the sensitivity of different taxonomic levels to environmental gradients in these lakes, and could possibly be integrated into a single numerical indicator similar to the RoiferTLI.

4 Discussion

4.1 Variability of water quality variables

The sampling frequency in the Waikato shallow lakes monitoring program (i.e. three times between December and May) is inadequate to accurately determine the mean value of variables for this period. The analysis of variability has shown that the error in the mean value for N=3 can exceed 1 (i.e. 100%). There is currently sufficient evidence to suggest that the seasonal spread of data collection does not captures the most stressful annual conditions experienced within the lakes. Trophic state variables outside the six-months period between December and May could potentially be an order of magnitude or more different from the currently assigned values, depending on the variable monitored. There is no evidence that any one of the indicators currently being used as part of the shallow lakes indicator project is likely to be more sensitive/responsive to improvement and/or decline in lake water quality.

An obvious implication of this review is that several years of data are needed to provide even moderately precise estimates of lake trophic state. Based on the shallow lakes' data analysis presented here, it is recommended that it would be most valuable to keep any lake on the monitoring program which has already multiple years of existing data (e.g. 3+ years). Based on this criterion alone and irrespective of any other monitoring programs, the candidate lakes are: Harihari, Mangahia, Maratoto, Ngahewa, Ohinewai, Okowhao, Otamatearoa, Rotomanuka, Serpentine East, Serpentine North, Serpentine South, Taharoa, Tutaeinanga, Waahi, Waikare, Whangape. It is not recommended to reduce sampling frequency in any of the lakes. It is also recognized, however, that several lakes in the Waikato Region have never been sampled. To determine the state of these lakes, it may be reasonable to rotate a number of lakes in the sampling regime, but this number should be small to ensure a long-term record for as many lakes as possible. Remote sensing may be useful to estimate trophic state in some presently unmonitored lakes but confounding effects due to lake size and bottom reflectance, as well as the relative infancy of this technique is unlikely to produce a complete coverage across the unmonitored lakes.

There is a certain degree of redundancy between the Waikato shallow lakes indicator program and the eight lakes long term monitoring program (see Table 1); both programs include sampling for trophic state indicators. The eight lakes monitoring program is mostly carried out on a monthly basis for trophic state variables, however, does not include regular monitoring of biological water quality indicators, such as the Rotifer TLI. If it is possible to collect zooplankton samples as part of the eight lakes

monitoring program for periods during which zooplankton samples are usually collected as part of the shallow lakes indicator program (i.e. December, March, May), then these eight lakes could be excluded from the shallow lakes indicator program.

4.2 Comparison of TLI vs. Rotifer TLI

The assessment of Rotifer TLI requires the measure of only one factor and could therefore potentially have the advantage of saving costs and time for measuring water quality in lakes compared to the conventional TLI (Duggan et al., 2001). It is argued, however, that determining the Rotifer TLI requires people with high quality taxonomic skills to identify many of the taxa which are included in the index, whereas the components for the conventional TLI can readily be analysed.

The Rotifer TLI does not necessarily reproduce the TLI, and thus the nutrient status, of a lake and this difference becomes more accentuated at low values (i.e. <3 or oligotrophic). While the development of the Rotifer TLI included several lakes within the oligotrophic category (mostly from the Bay of Plenty Region), the response of the rotifer community structure to oligotrophic Waikato shallow lakes may be somewhat different and this group may not demonstrate the same level of sensitivity to low-nutrient waters as shown by Duggan et al. (2001). Thus responses of Rotifer TLI to re-oligotrophication or at least to water quality improvement, may be different to those of the TLI. There was no statistically significant indication that the predictive power of the Rotifer TLI would be stronger or weaker for different lake types, though TLI values for dune lakes in particular were generally under-predicted. As outlined by Duggan et al. (2001), the rotifer species' distributions could potentially be influenced by a number of factors other than nutrient status of lakes. Examples of Rotifer TLI influences that may be more accentuated than the corresponding TLI change may include the appearance of toxic cyanobacteria (Starkweather & Kellar, 1987), predation pressure by larger zooplankton (Pejler, 1983) and bottom-water oxygen depletion (Mikschi, 1989). A comprehensive analysis as to why the Rotifer TLI does not predict the TLI with higher accuracy in the Waikato shallow lakes was outside the scope of this review, but may be useful. It is recommended that the relationships between TLI and Rotifer TLI used in Duggan et al. (2001) are validated at a species level using the more contemporary data used in this study. Alternatively, the relationship developed in this study for the Waikato lakes could be used in future for predicting TLI values but should be refined further with time.

As a biological indicator, the Rotifer TLI is currently the only indicator included in the Waikato shallow lakes program at a regular sampling interval, whilst macrophyte surveys to determine LakeSPI are carried out only intermittently. It is important to recognise the significance of biological indicators in an integrated approach to determine overall lake health, and with zooplankton having a central role in aquatic ecosystem between primary producers and higher organisms, it is essential to complement any future trophic state monitoring in the Waikato shallow lakes with the Rotifer TLI.

4.3 Evidence of regime shifts and/or alternative stable states

Conclusions about existence of regime shifts, with associated alternative stable states, cannot be made from Waikato shallow lakes available in this study though there is indirect evidence provided in comparison amongst some variables. Literature on alternative stable states in ecological systems suggests that it is difficult to conclusively determine alternative stable states using field data, even if time series data are comprehensive (Scheffer and Carpenter, 2003). Only one of three lines of evidence (Scheffer and Carpenter, 2003) was used in this study to understand patterns of trophic state variables in vegetated and non-vegetated lakes. Different indicators of alternative stable states were not able to be explored for this study due to the low temporal resolution of the data set. Increases in variability, both in terms of magnitude and frequency of variation have been suggested to be a precursor of regime shifts

(Carpenter and Brock, 2006). However, given the inherent background variability in the Waikato shallow lakes, long-term data for individual lakes are required to determine, for example, critical turbidities, or precursors to a regime shift.In this study, macrophyte survey data were categorised broadly into vegetated and non-vegetated lakes, and consequently, values of trophic state indicators show overlap between these two categories. An analysis of changes in species or taxa of aquatic vegetation may reveal more subtle differences between and/or within each of the two categories. Temporal resolution of macrophyte surveys, however, need to be consistent and synchronised across lakes and there may be a need to increase sampling frequency in lakes that are considered to 'flip' (sensu Schallberberg and Sorrell, 2009) or susceptible to a regime shift, which for most Waikato lakes has been uni-directional, from vegetated to non-vegetated.

References

Beutel MW 2001. Oxygen consumption and ammonia accumulation in the hypolimnion of Walker Lake, Nevada. Hydrobiologia 466: 107-117.

Bruns NM 1995. Using hypolimnetic dissolved oxygen depletion rates for monitoring lakes. New Zealand Journal of Marine and Freshwater Research 29: 1-11.

Burns NM, Rutherford JC, Clayton JS 1999. A monitoring and classification system for New Zealand lakes and reservoirs. Lake and Reservoir Management 15: 255-271.

Carpenter SR, Brock WA 2006. Rising variance: a leading indicator of ecological transition. Ecology Letters 9: 311-318.

Chapra SC, Carnale RP 1991. Long-term phenomenological model of phosphorus and oxygen in stratified lakes. Water Research 25(6): 707-715.

Duggan IC, Green JD, Shiel RJ 2001. Distribution of rotifers in North Island, New Zealand, and their potential use as bioindicators of lake trophic state. Hydrobiologia 446/447: 155-164.

Edwards T, de Winton M, Clayton J 2009. Assessment of the ecological condition of lakes in the Waikato region using LakeSPI - 2009. Environment Waikato Technical Report 2009/14. Hamilton, Waikato Regional Council (Environment Waikato)

Gelda RK, Auer MT, Effler SW 1995. Determination of sediment oxygen demand by direct measurement and by interference from reduced species accumulation. Marine and Freshwater Research 46: 81-88.

Hamilton DP, Duggan IC 2010. Plankton. Chapter 7. In: Collier KJ, Hamilton DP, Vant W, Howard-Williams C eds. Waters of the Waikato: ecology of New Zealand's longest river. Hamilton, Environment Waikato/University of Waikato, 117-132.

Hutchison GE 1957. A treatise on limnology, volume 1: geography, physics and chemistry. New York, John Wiley and Sons.

Kalff J 2003. Limology. New York, Prentice-Hall

Kolar CS, Rahel FJ 1993. Interaction of a biotic factor (predator presence) and an abiotic factor (low oxygen) as an influence of benthic invertebrate communities. Oecologia 95: 210-219.

McBride GB, Smith DG 1997. Sampling and analytical tolerances requirements for detecting trends in water quality. Journal of the American Water Resource Association 33(2): 367-373.

Mikschi E 1989. Rotifer distribution in relation to temperature and oxygen content. Hydrobiologia 186/187: 209-214.

Ostapenia AP, Parparov A, Berman T 2009. Lability of organic carbon in lakes of different trophic status. Freshwater Biology 54: 1312-1323.

Pacheco JP, Iglesias C, Meerhoff M, Fosalba C, Goyenola G, Teixeira-de Mello F, García S, Gelós M, García-Rodríguez F 2010. Phytoplankton community structure in five subtropical shallow lakes with different trophic status (Uruguay): a morphology-based approach. Hydrobiologia 646: 187-197.

Padisák J, Crossetti LO, Naselli-Flores L 2009. Use and misuse in the application of the phytoplankton functional classification: a critical review with updates. Hydrobiologia 621: 1-19.

Paul W, Ostrovsky I, Hamilton D, Miller S. Zhang A, Muraoka K 2011. Catchment land use and trophic status impacts on phytoplankton composition: A case study from the Rotorua lakes' district, New Zealand. Hydrobiologia, submitted.

Pejler B 1983. Zooplanktic indicators of trophy and their food. Hydrobiologia 101: 111-114.

Ryan EF, Duggan IC, Hamilton DP, Burger DF 2006. Phytoplankton assemplages in North Island lakes of New Zealand: is trophic state, mixing or light climate more important? New Zealand Journal of Marine and Freshwater Research 40: 389-398.

Schallenberg M, Sorrel B 2009. Regime shifts between clear and turbid water in New Zealand lakes: environmental correlates and implications for management and restoration. New Zealand Journal of Marine and Freshwater Research 43: 701-712.

Scheffer M, Carpenter SR 2003. Catastrophic regime shifts in ecosystems: linking theory to observation. Trends in Ecology and Evolution 18(12): 648-656

Søndergaard M, Jensen JP, Jeppesen E 2003. Role of sediment an internal loading of phosphorus in shallow lakes. Hydrobiologia 506-509: 135-145.

Stakweather PL, Kellar PE 1987. Combined influence of particulate and dissolved factors in the toxicity of *Microcystis aeruginosa* (NRC-SS-17) to the rotifer *Brachionus calyciflorus*. Hydrobiologia 147: 375-378.

Villegas I, DeGiner G 1973. Phytoplankton as a biological indicator of water quality. Water Research Pergamon Press 7: 479-487.

Appendices

Appendix I: Water quality monitoring methodology and sampling (Waikato Regional Concil).

Appendix II: Annual CV values of different water quality variables.

Appendix III: Seasonal CV values of different water quality variables.

Appendix IV: Monthly CV values of different water quality variables.

Appendix V: Compilations of CV values across different temporal scales

Appendix VI: Probability distributions for trophic state variables in 8 lakes

Appendix I: Water quality monitoring methodology and sampling (Waikato Regional Council).

General:

Sampling sites should be as close to the deepest part of the lake. GPS co-ordinates as well as visual location (landmarks and photographs) to be used to re-position in correct sampling location.

(1) Secchi Disk

Lower disc into water on sunny side of boat.
Two measurements need to be recorded – depth at which secchi disc disappears (secchi disc A) and the depth at which secchi disc reappears (secchi disk B).
A mean depth is calculated from the two readings.
The two observations should be within 10% of each other.

(2) Status of Lake

Isothermal

A guideline for the isothermal status is if the surface and bottom temperatures are within 3 degrees Celsius of each other. If isothermal **only one** sample is to be taken (ISO-T)

ISO-T = taken at ¼ max depth of lake.
Use Van Dorne sampler – take 3 samples of water at ¼ depth and combine in a bucket.
Sub-sample two x 1 litre bottles from this mix.
Also fill 1 x TKN small sample bottle from this mix.
Rinse bucket with some of sample prior to filling.

Stratified

Three layers exist within the stratified lake and are defined as the following:
Epilimnion – relatively well mixed upper layer, extends to above the bottom – epi knee (change in temp).
Thermocline – rapid change of temperature with depth.
Hypolimnion – where thermocline becomes the hypolimnion and there is a slower change of temperature with depth.

If stratified two samples to be taken (EPI and either HYP-T or HYP-B/X):

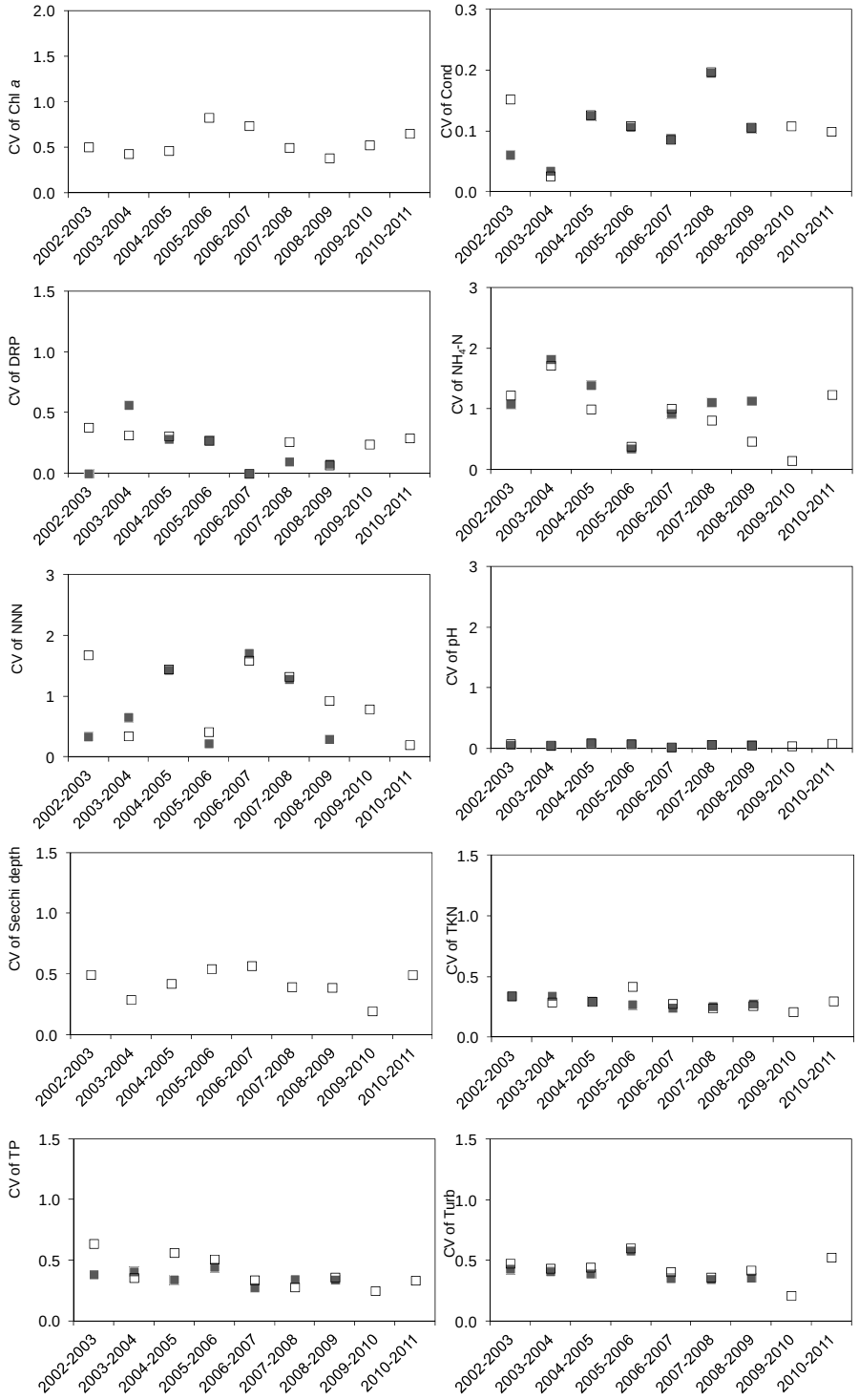
EPI = taken at 0.2m, ¼, ½ and ¾ depth of epilimnion
Use Van Dorn sampler – take 4 samples of water at 1.2, ¼, ½ and ¾ depth of epilimnion and combine in a bucket. Sub-sample two x 1 litre bottles from this mix.
Also fill 1 x TKN small sample bottle from this mix
Rinse bucket with some of sample prior to filling.

HYP-T = taken at ½ depth of the hypolimnion if this layer contains oxygen at all depths
Use Van Dorn sampler – take one sample of water at ½ layer depth and use a little to rinse out sample bottle. Fill 1 x 1 litre sample bottle and small TKN bottle.

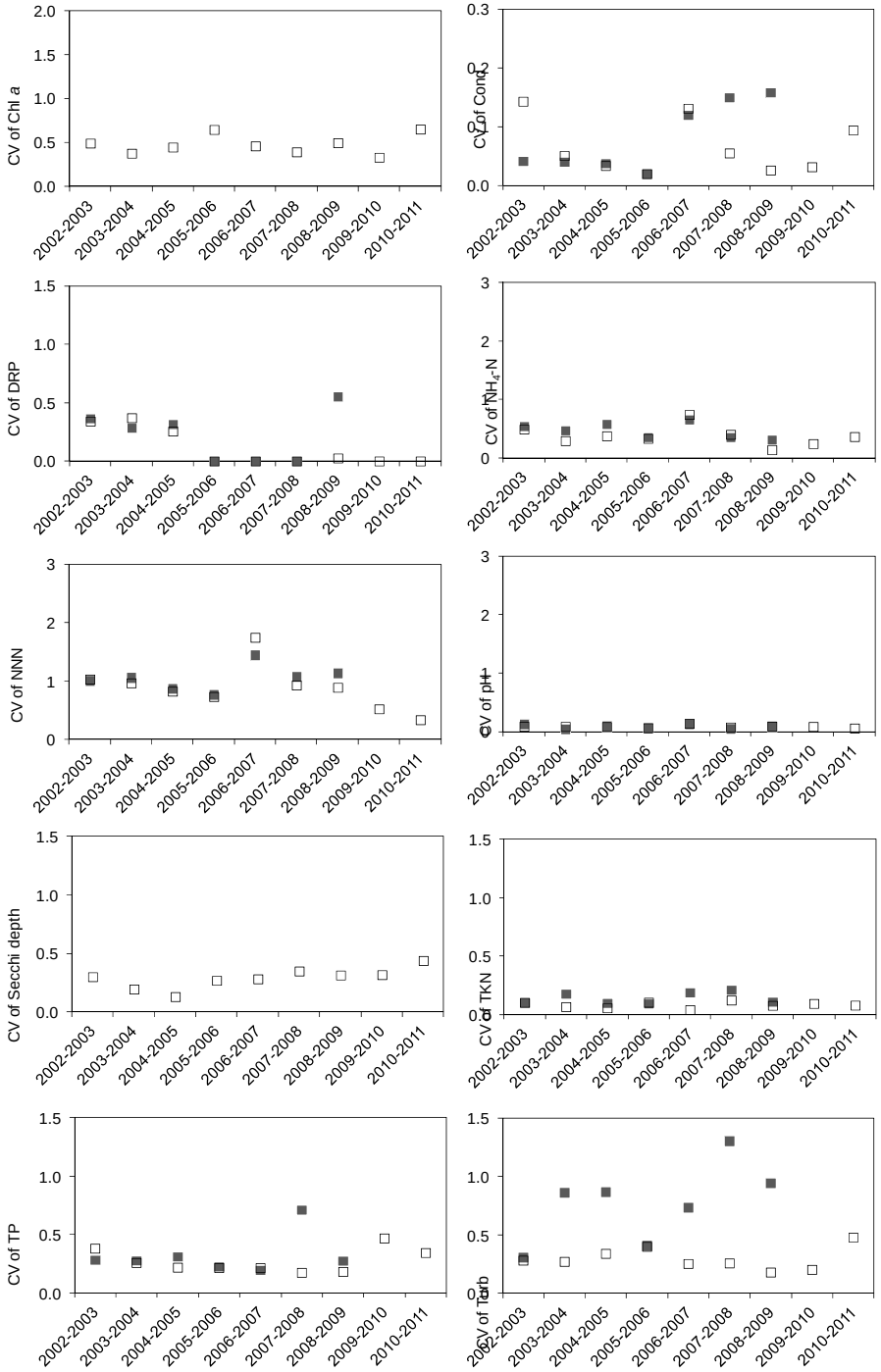
HYP-B/X = taken at mid-point of <3% DO zone (anoxic).
Only required if this zone exists
Use Van Dorn sampler – take one sample of water at ½ depth of this zone. Fill 1 x 1 litre sample bottle and small TKN bottle.

NB: ONLY TWO SAMPLES ARE TO BE TAKEN FROM ANY ONE LAKE – HYP-B/X TAKES PREFERENCE OVER HYP-T
Protocols are taken from the following guidelines:
Protocols for monitoring trophic levels of New Zealand Lakes and Reservoirs, Noel Burns of Lakes Consulting, Graham Bryers and Eddie Bowman of NIWA Hamilton.

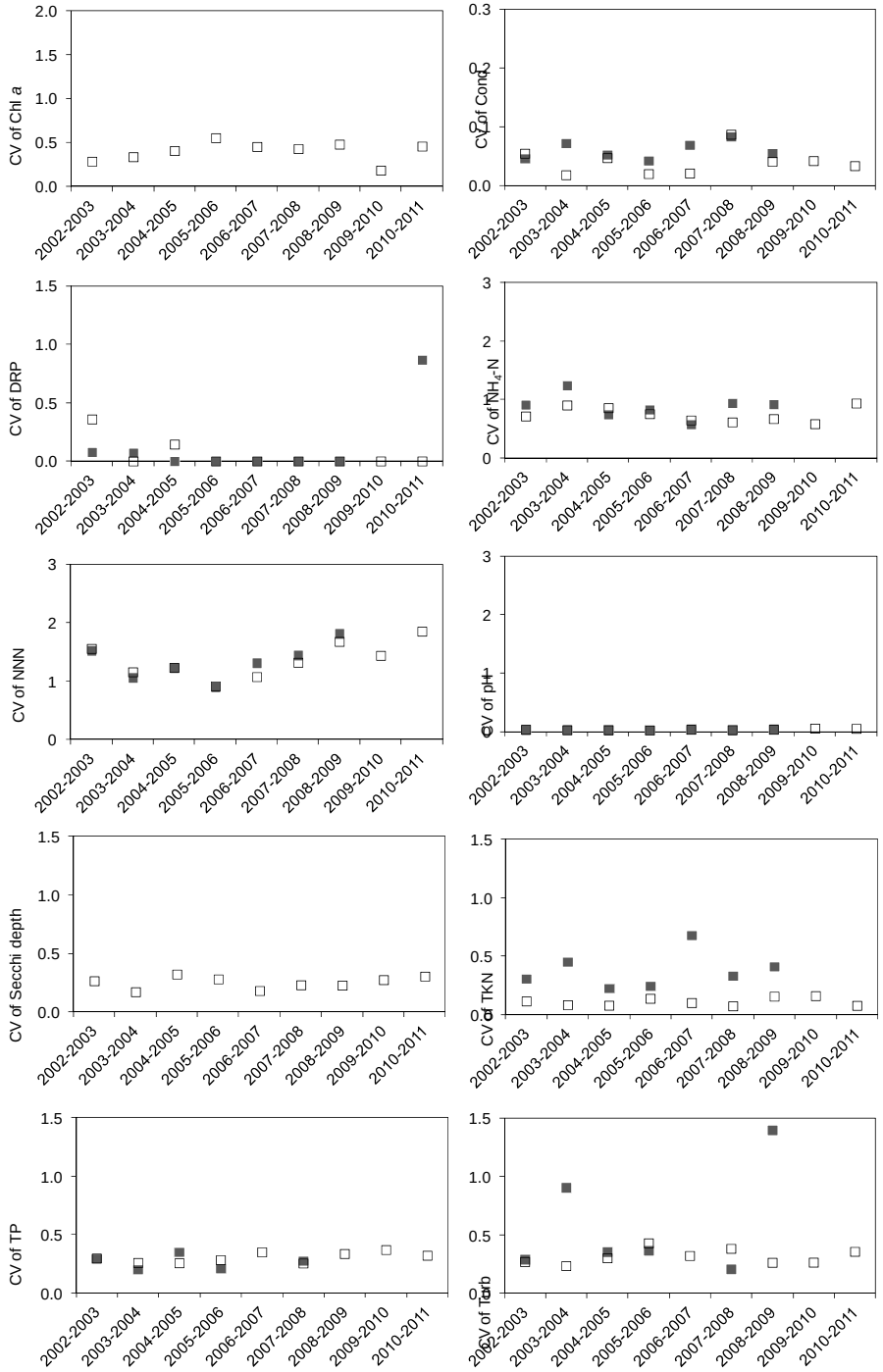
Appendix II: Annual CV values of different water quality variables.



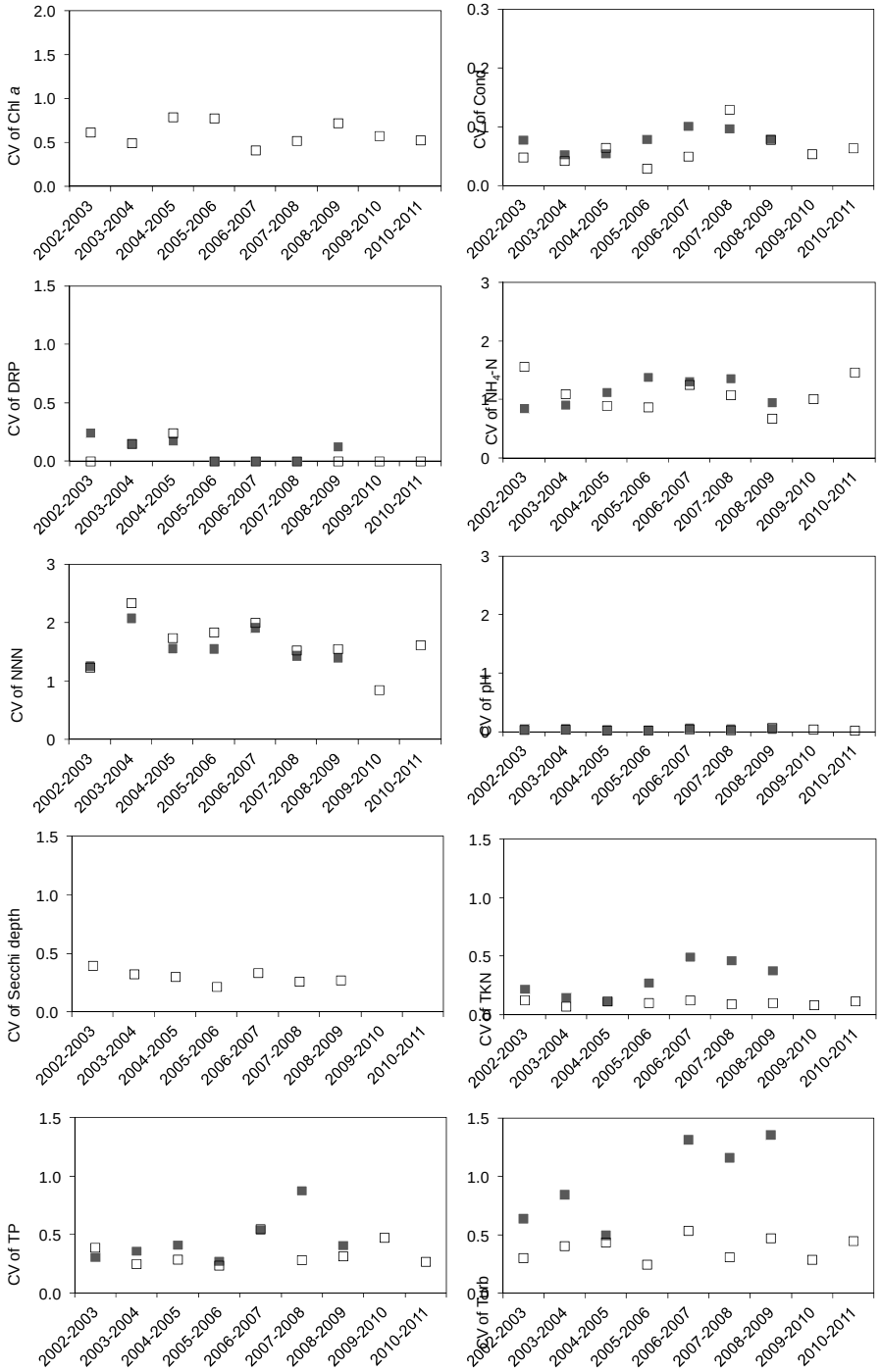
Appendix figure II.1: Annual CV values of different water quality variables for Lake Hakanoa. Empty squares are surface values and filled squares are bottom values.



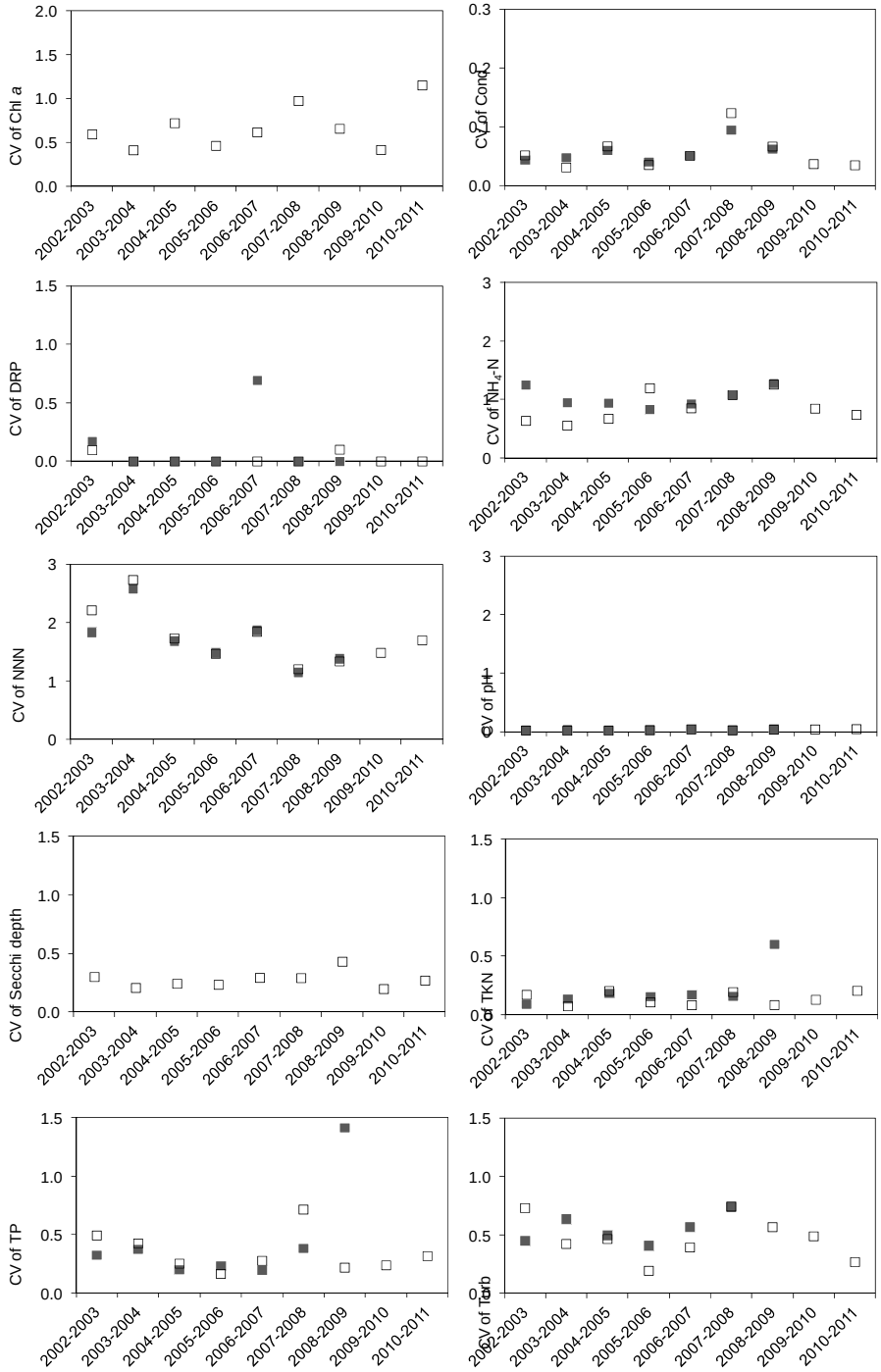
Appendix figure II.2: Annual CV values of different water quality variables for Lake Maratoto Empty squares are surface values and filled squares are bottom values.



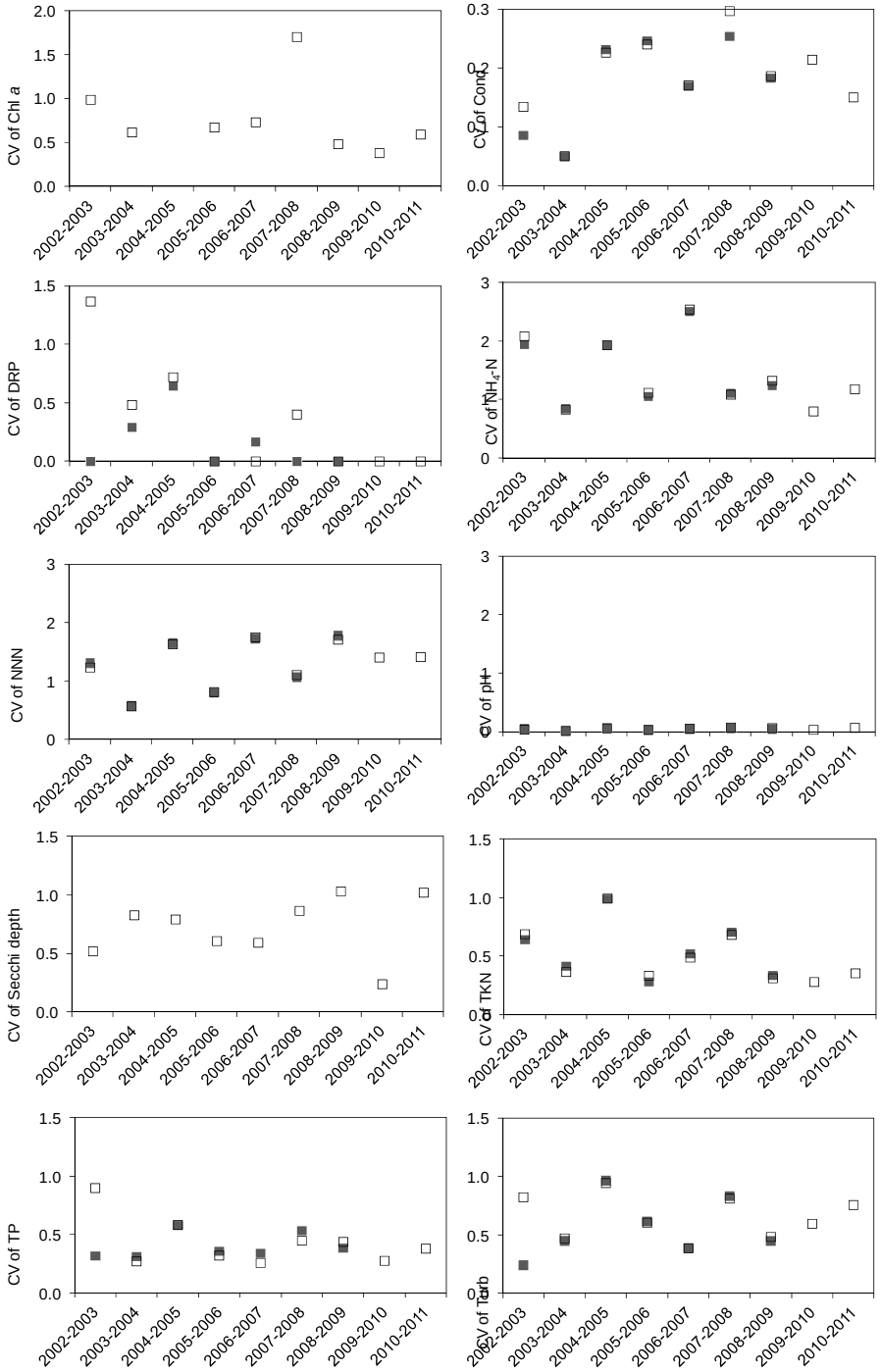
Appendix figure II.3: Annual CV values of different water quality variables for Lake Rotomanuka. Empty squares are surface values and filled squares are bottom values.



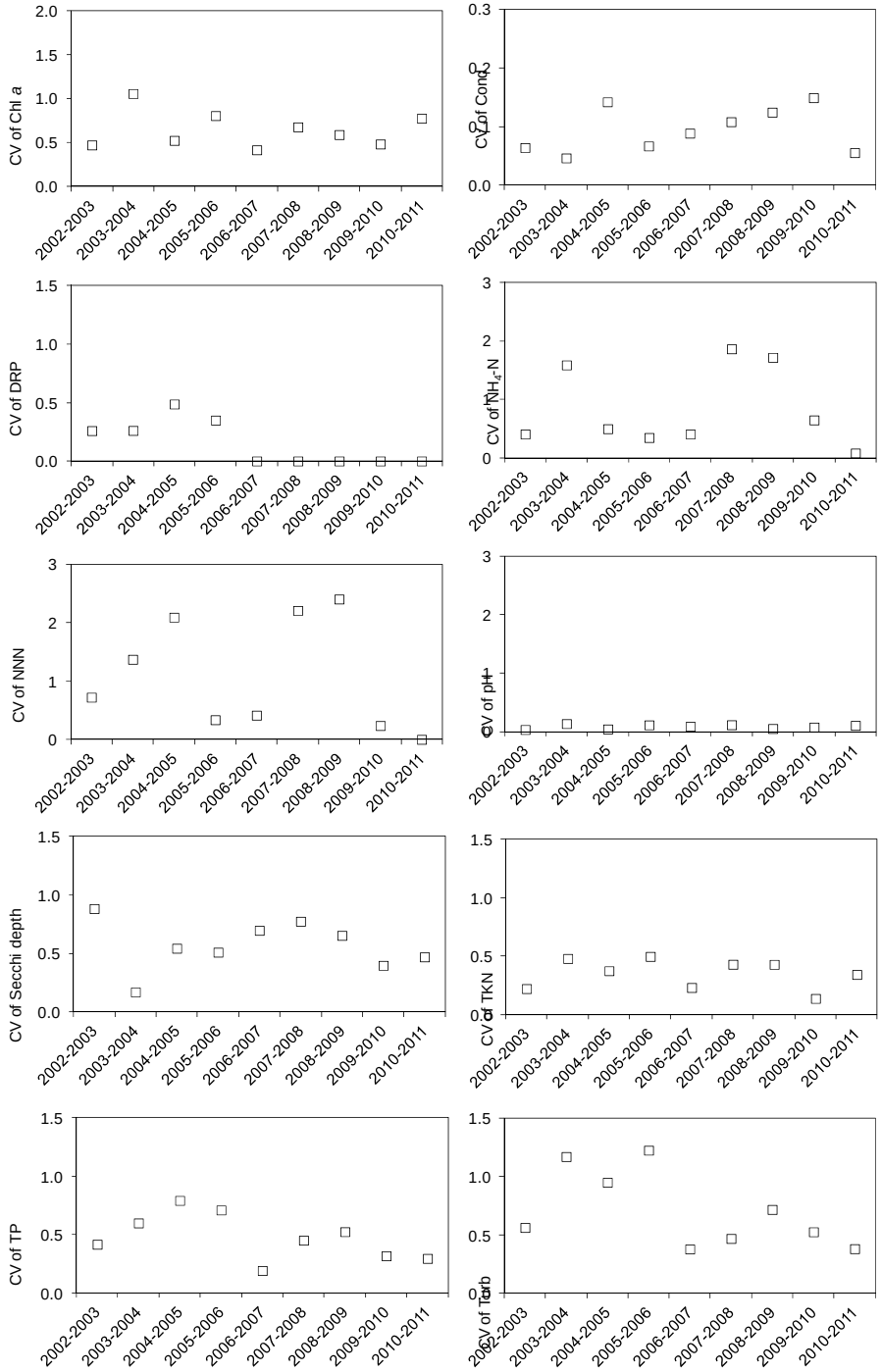
Appendix figure II.4: Annual CV values of different water quality variables for Lake Serpentine East. Empty squares are surface values and filled squares are bottom values.



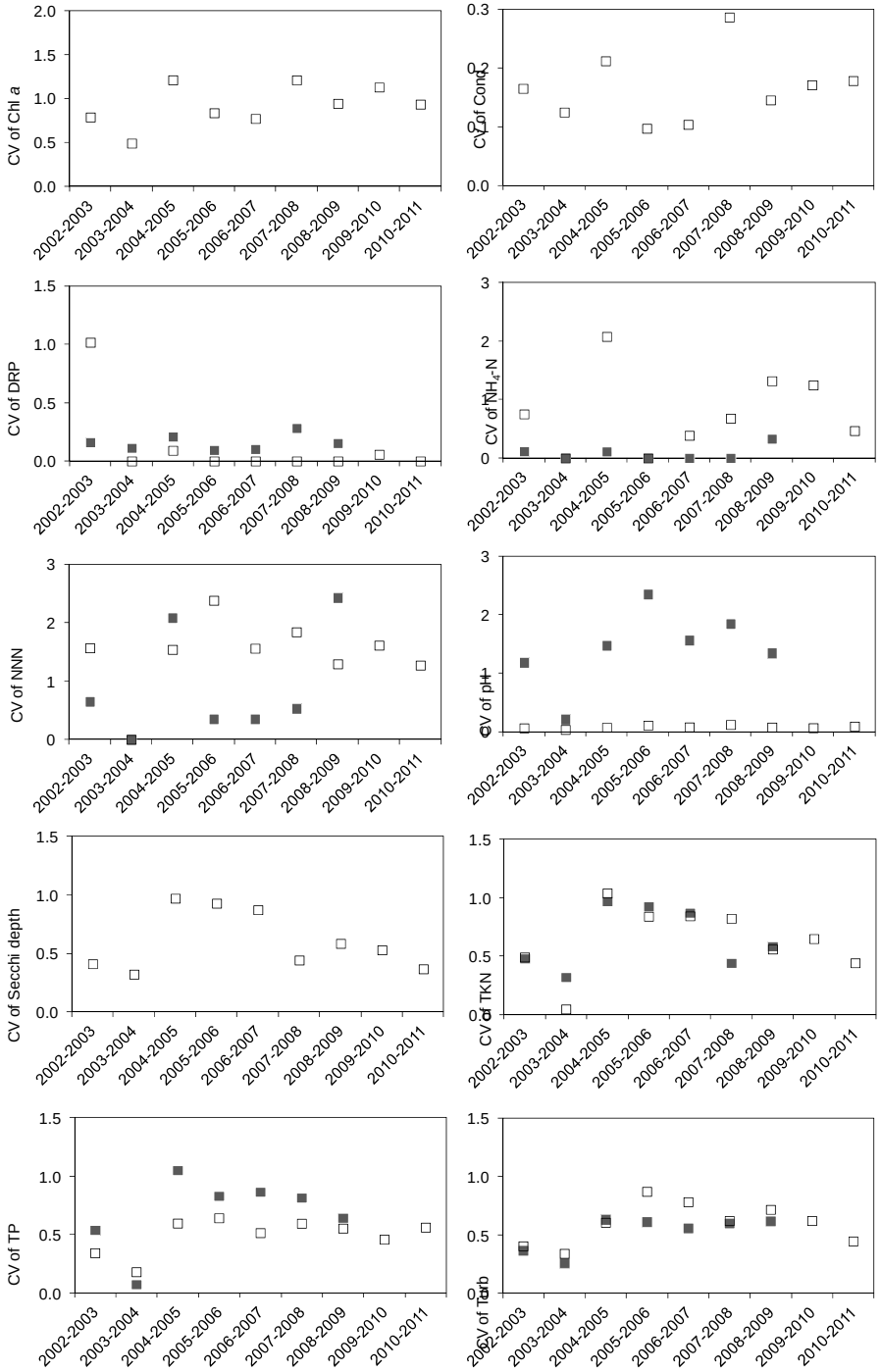
Appendix figure II.5: Annual CV values of different water quality variables for Lake Serpentine North. Empty squares are surface values and filled squares are bottom values.



Appendix figure II.6: Annual CV values of different water quality variables for Lake Waahi. Empty squares are surface values and filled squares are bottom values.

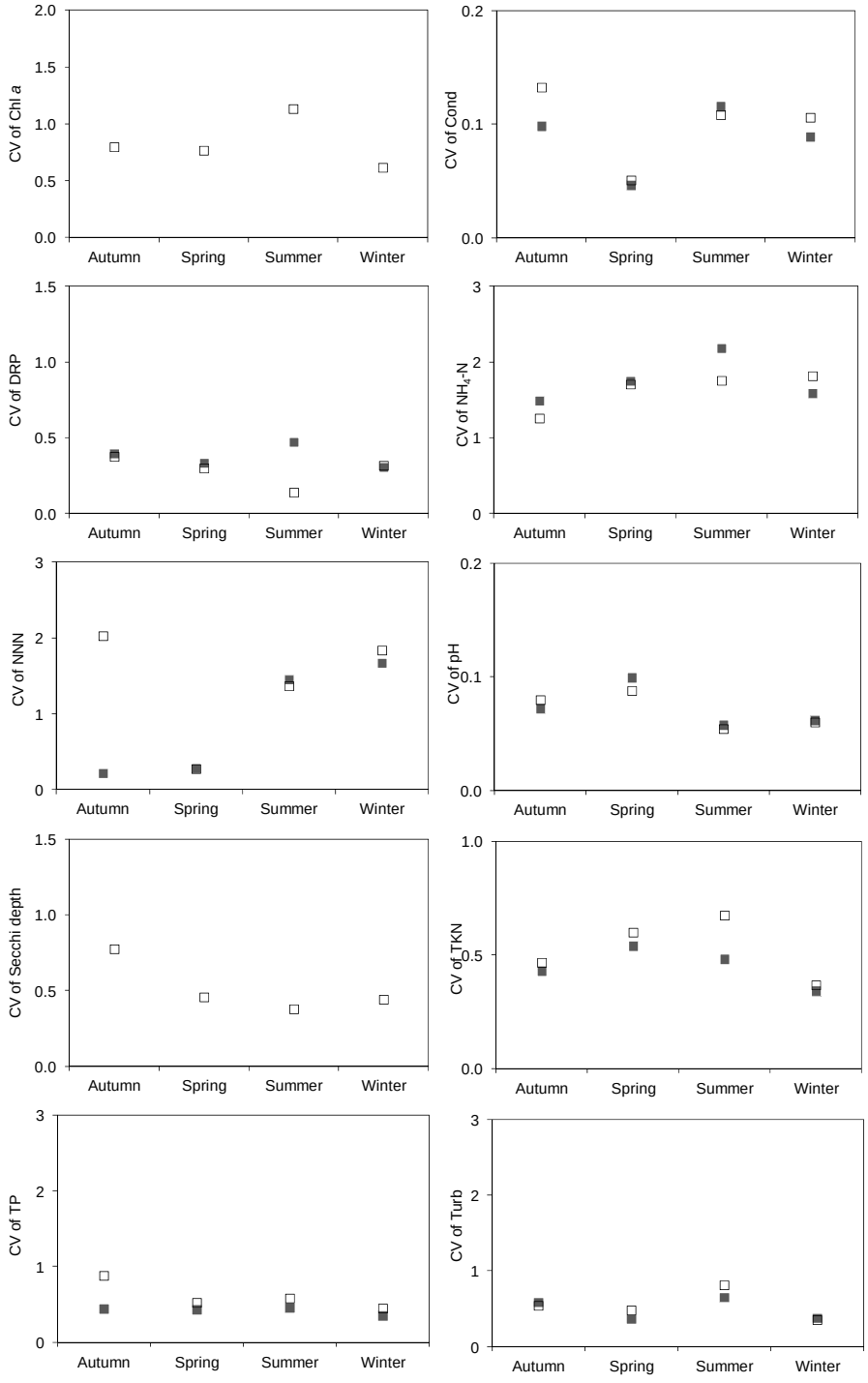


Appendix figure II.7: Annual CV values of different water quality variables for Lake Waikare. Empty squares are surface values and filled squares are bottom values.

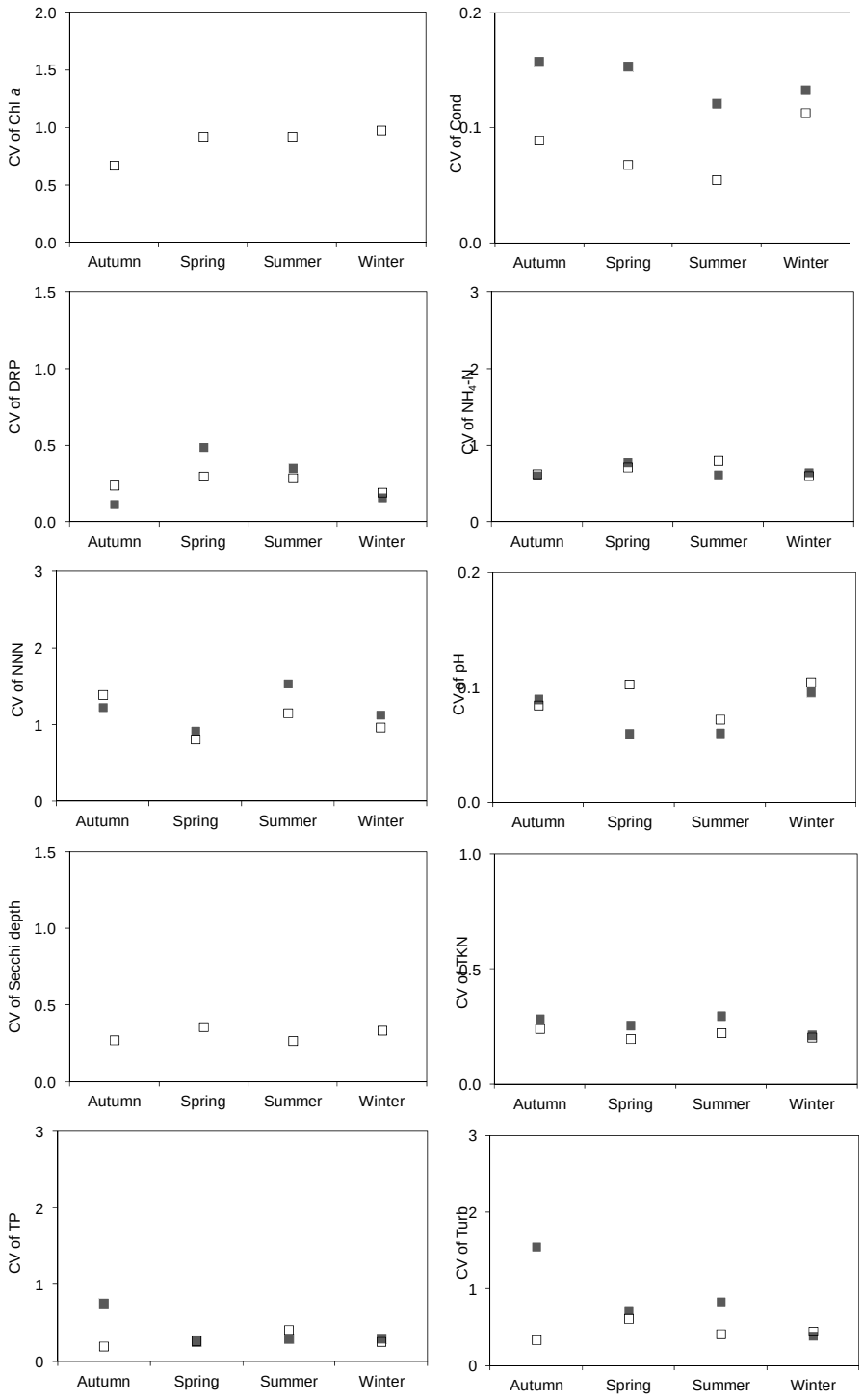


Appendix figure II.8: Annual CV values of different water quality variables for Lake Whangape. Empty squares are surface values and filled squares are bottom values.

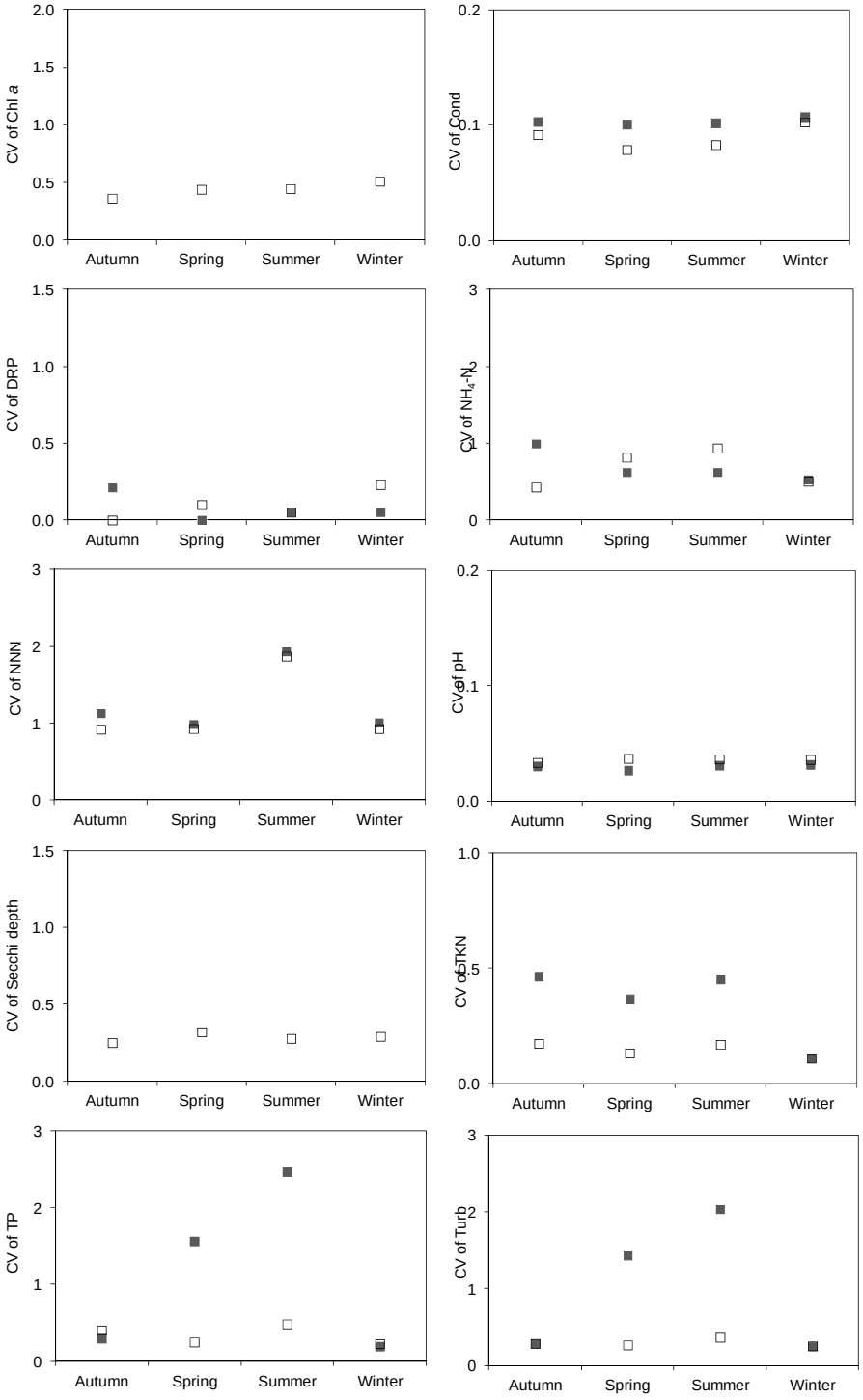
Appendix III: Seasonal CV values of different water quality variables.



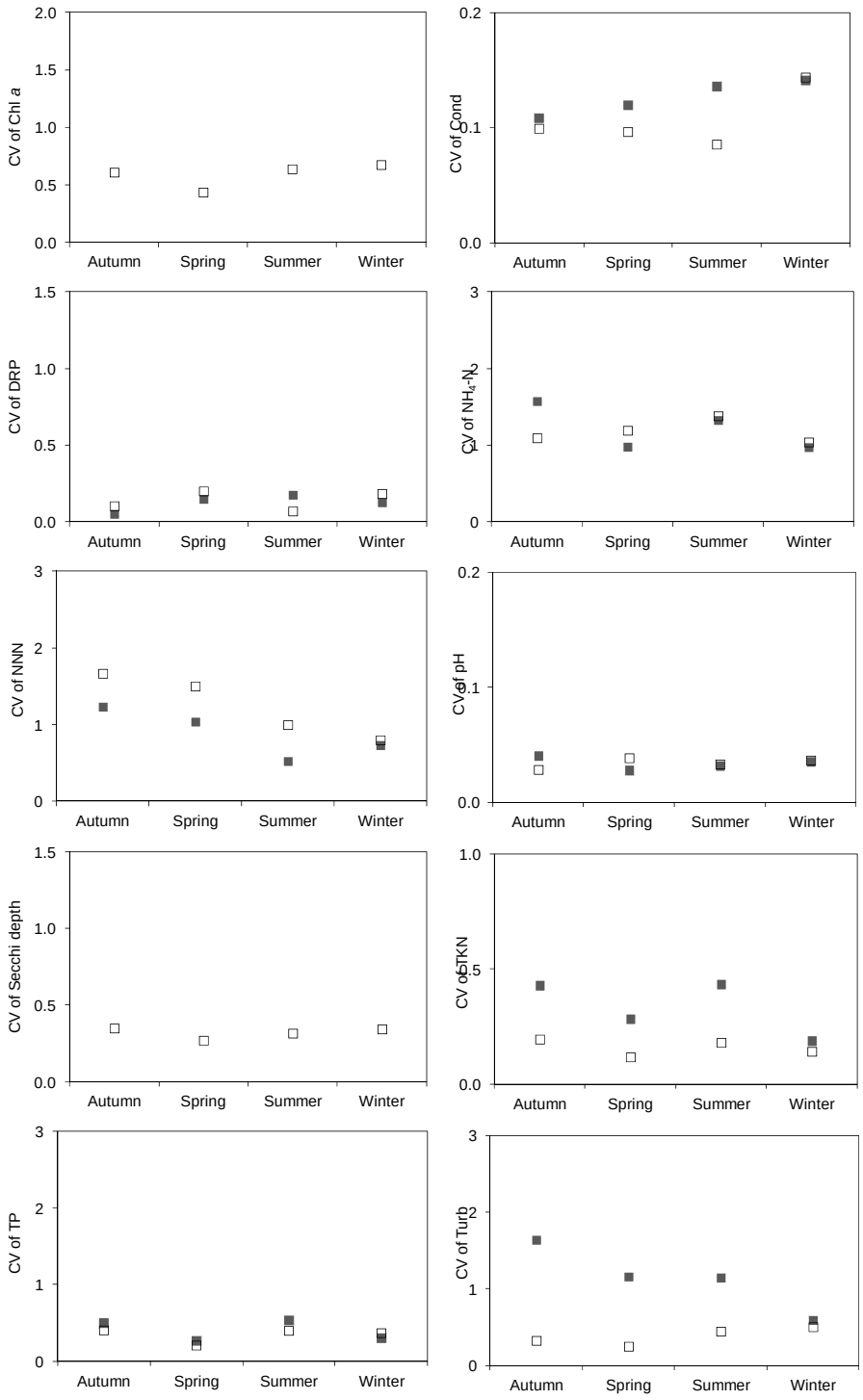
Appendix figure III.1: Seasonal CV values of different water quality variables for Lake Hakanoa. Empty squares are surface values and filled squares are bottom values.



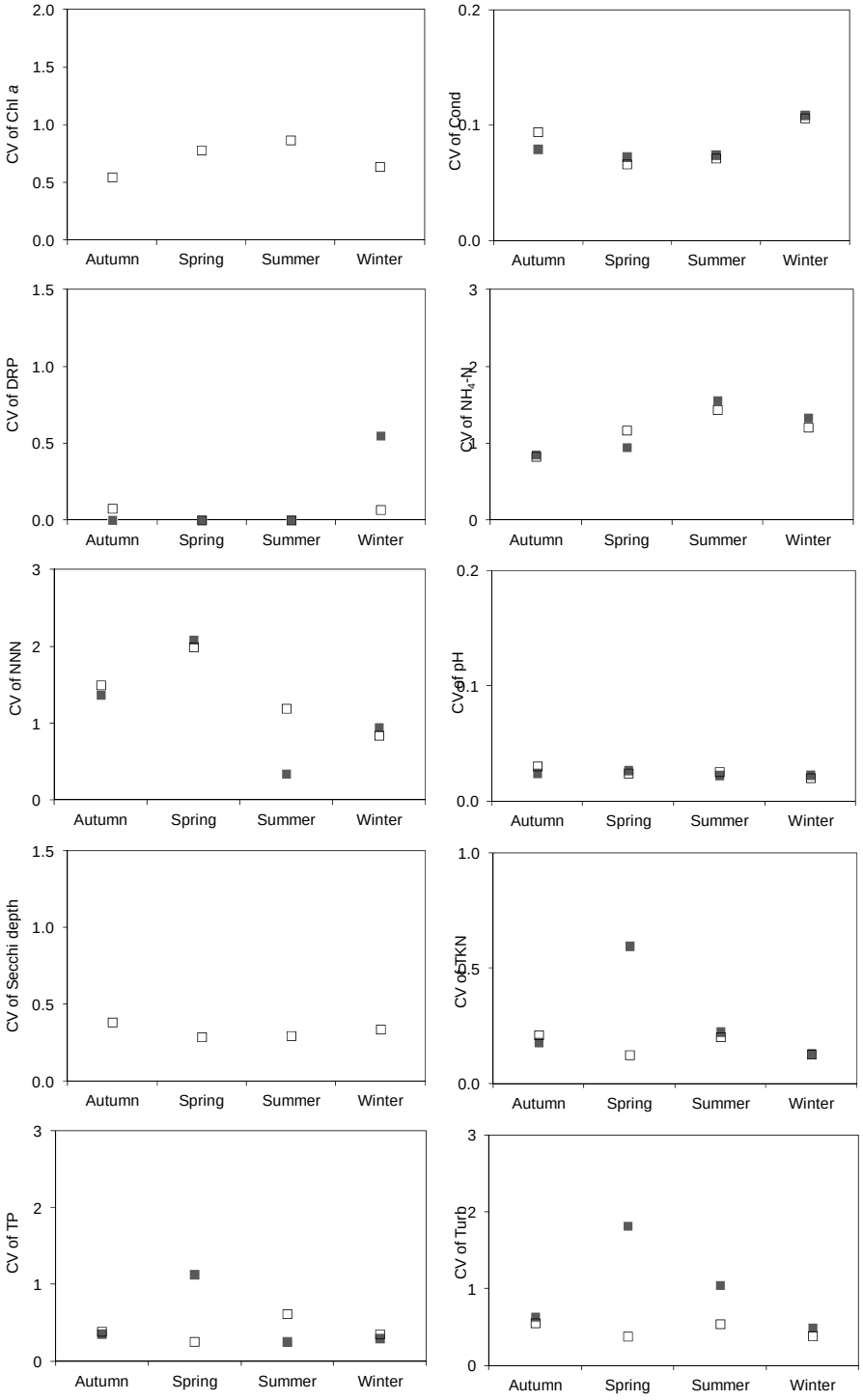
Appendix figure III.2: Seasonal CV values of different water quality variables for Lake Maratoto. Empty squares are surface values and filled squares are bottom values.



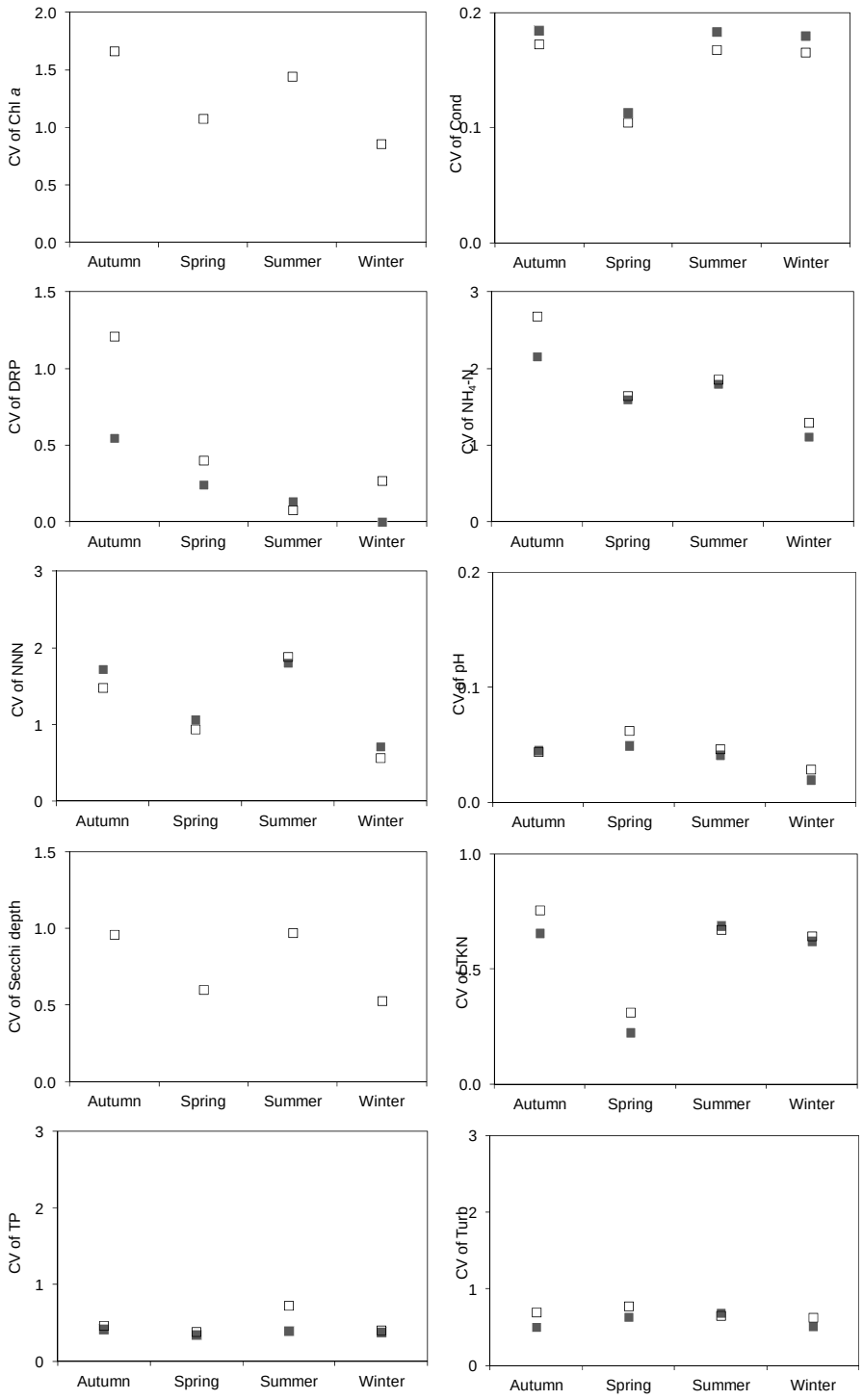
Appendix figure III.3: Seasonal CV values of different water quality variables for Lake Rotomanuka. Empty squares are surface values and filled squares are bottom values.



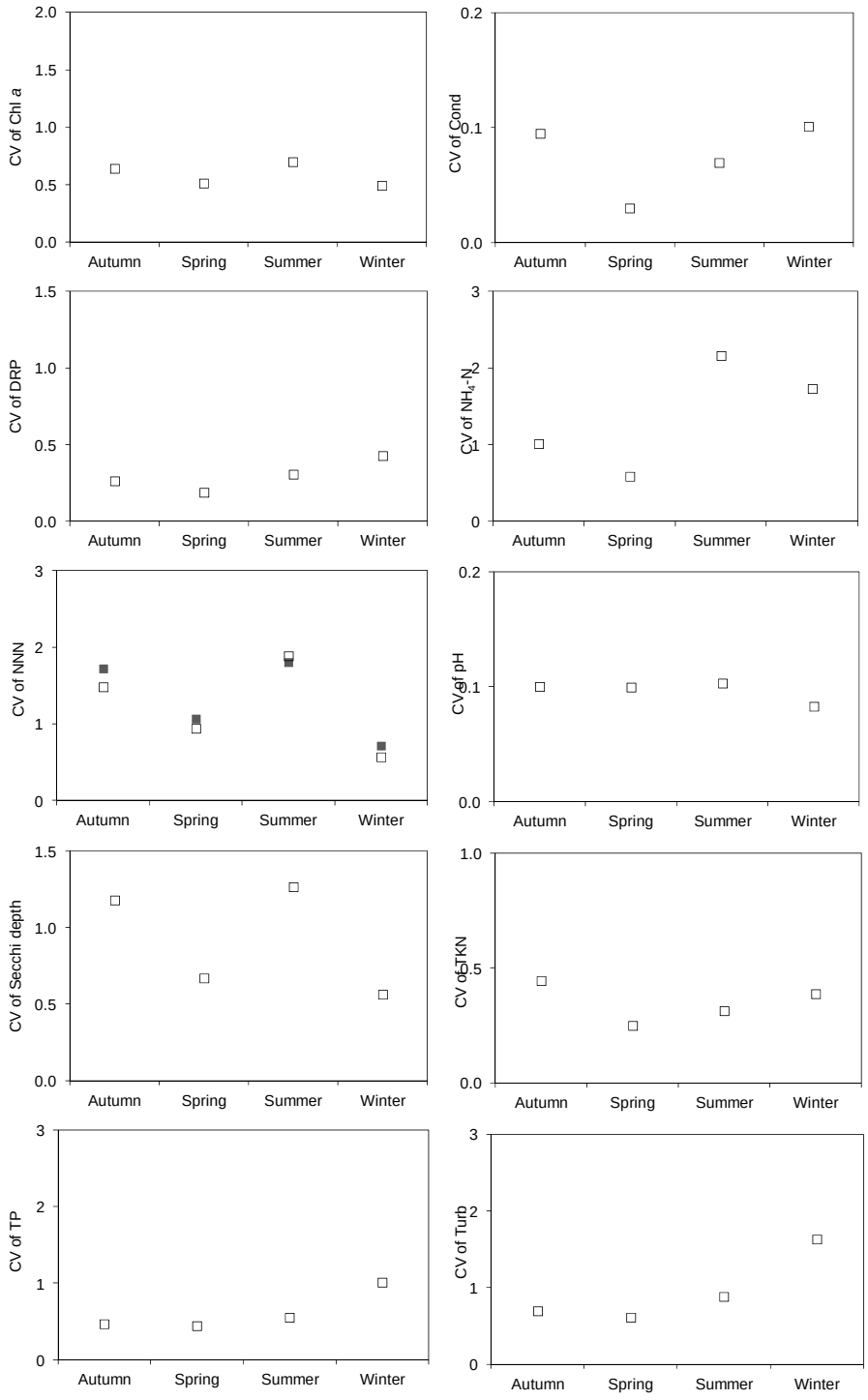
Appendix figure III.4: Seasonal CV values of different water quality variables for Lake Serpentine East. Empty squares are surface values and filled squares are bottom values.



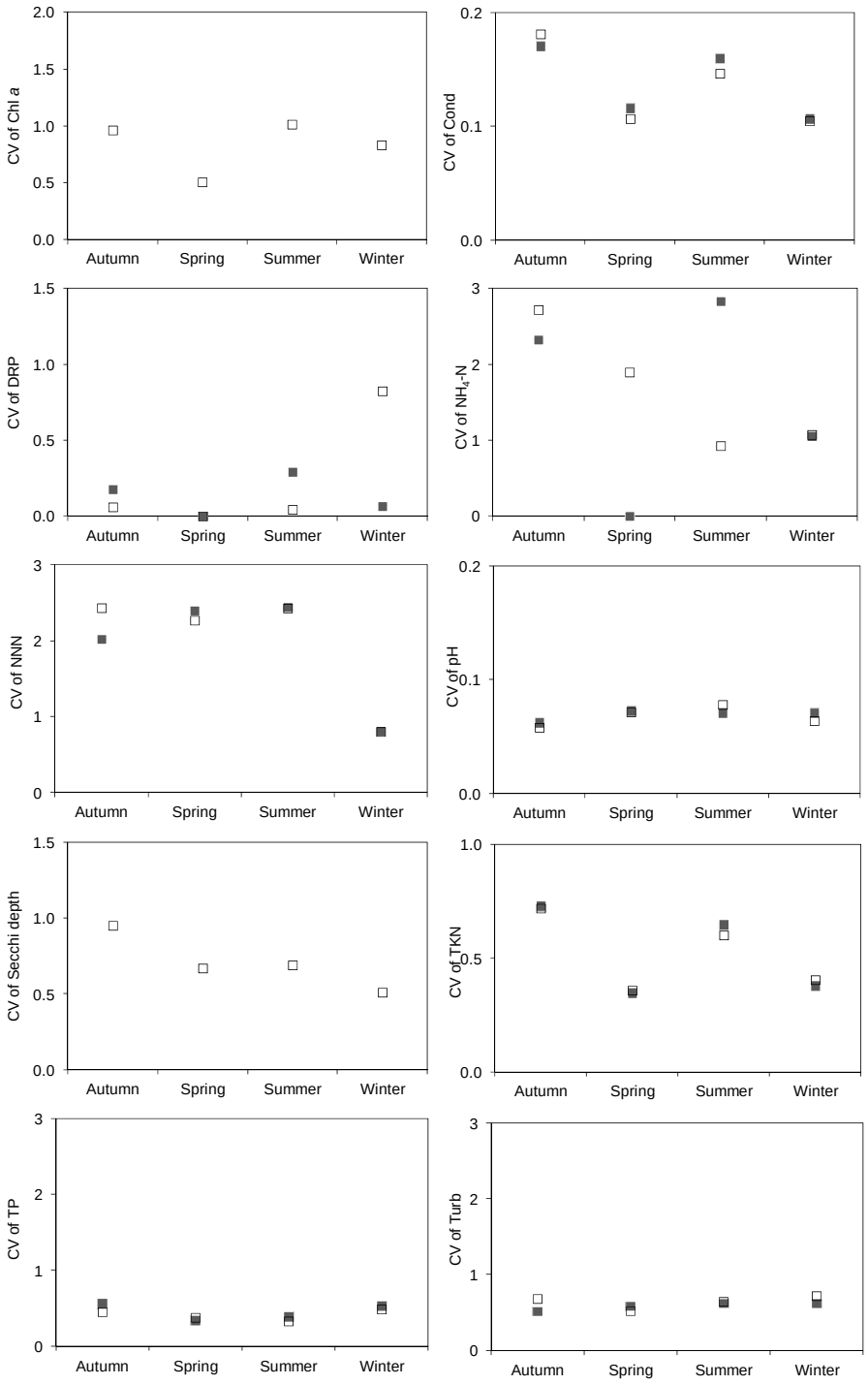
Appendix figure III.5: Seasonal CV values of different water quality variables for Lake Serpentine North. Empty squares are surface values and filled squares are bottom values.



Appendix figure III.6: Seasonal CV values of different water quality variables for Lake Waahi. Empty squares are surface values and filled squares are bottom values.

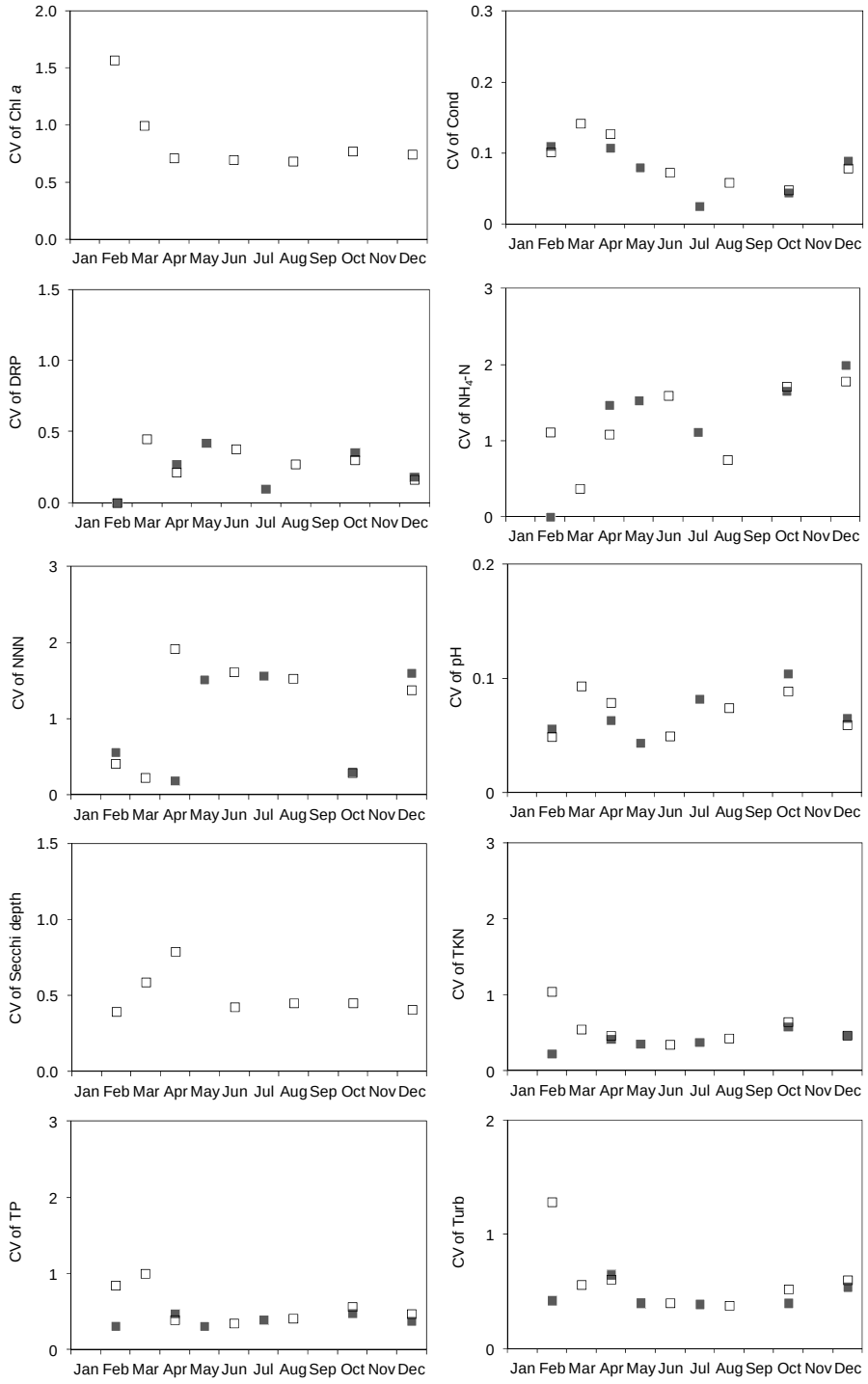


Appendix figure III.7: Seasonal CV values of different water quality variables for Lake Waikare. Empty squares are surface values and filled squares are bottom values.

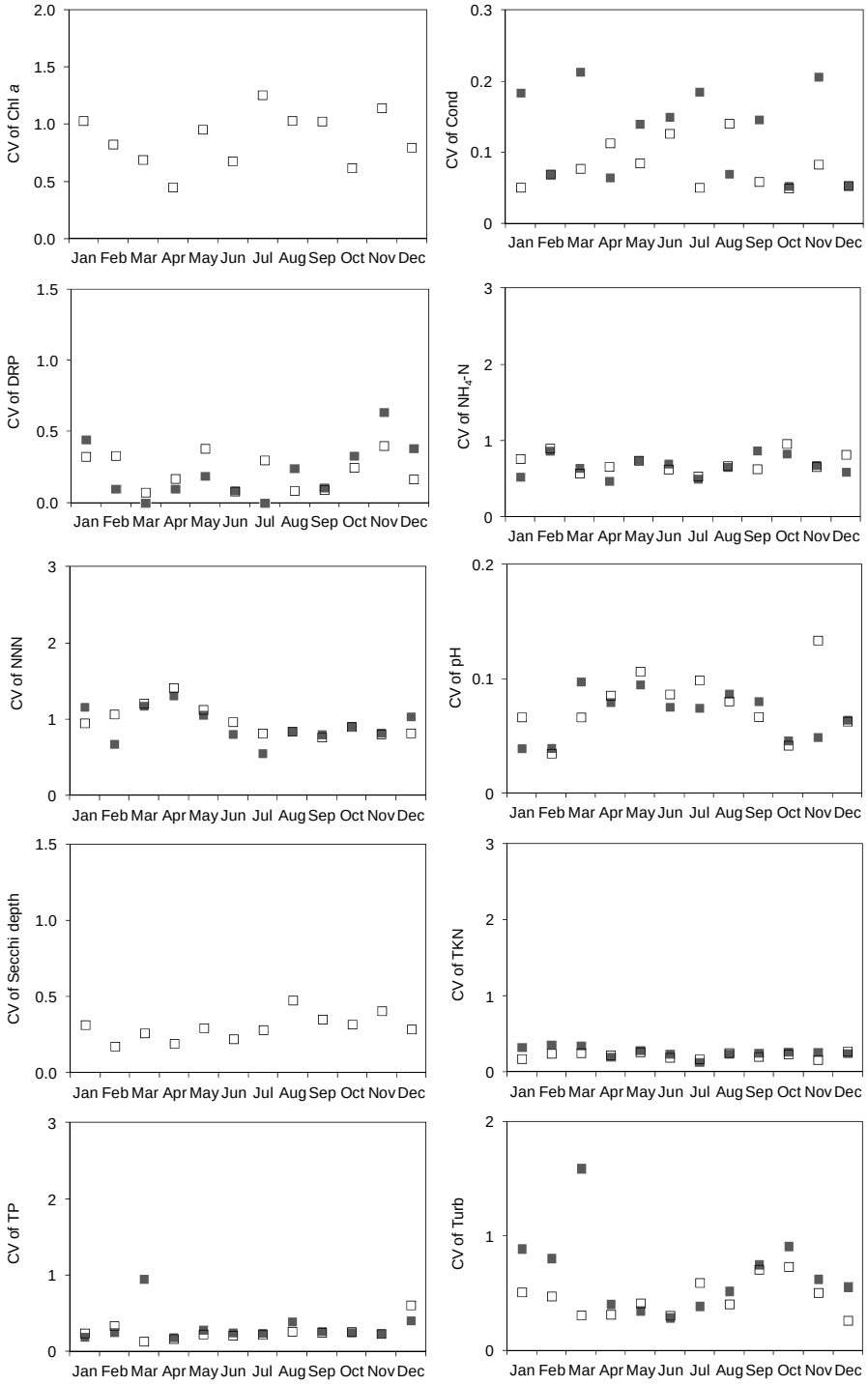


Appendix figure III.8: Seasonal CV values of different water quality variables for Lake Whangape. Empty squares are surface values and filled squares are bottom values.

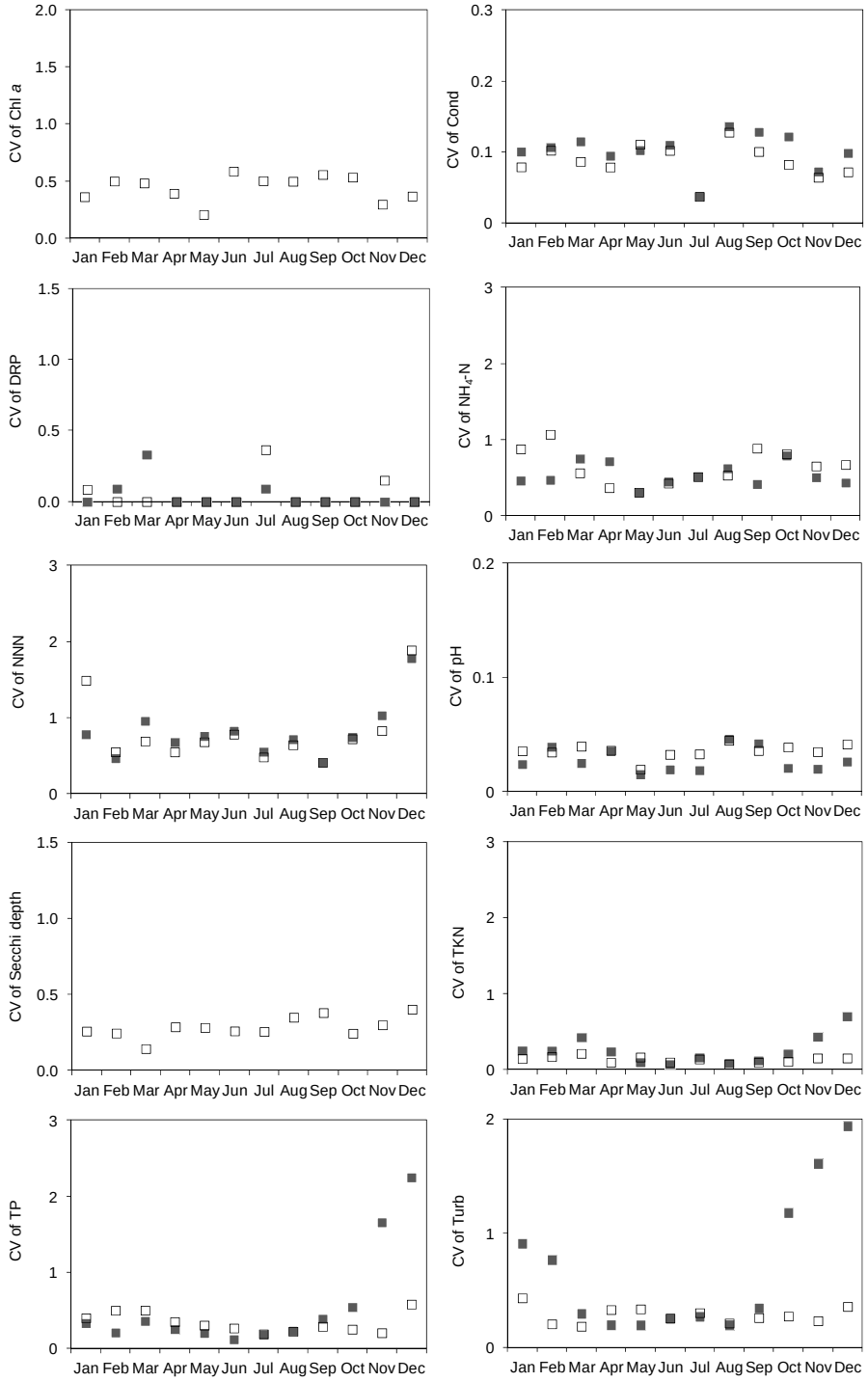
Appendix IV: Monthly CV values of different water quality variables.



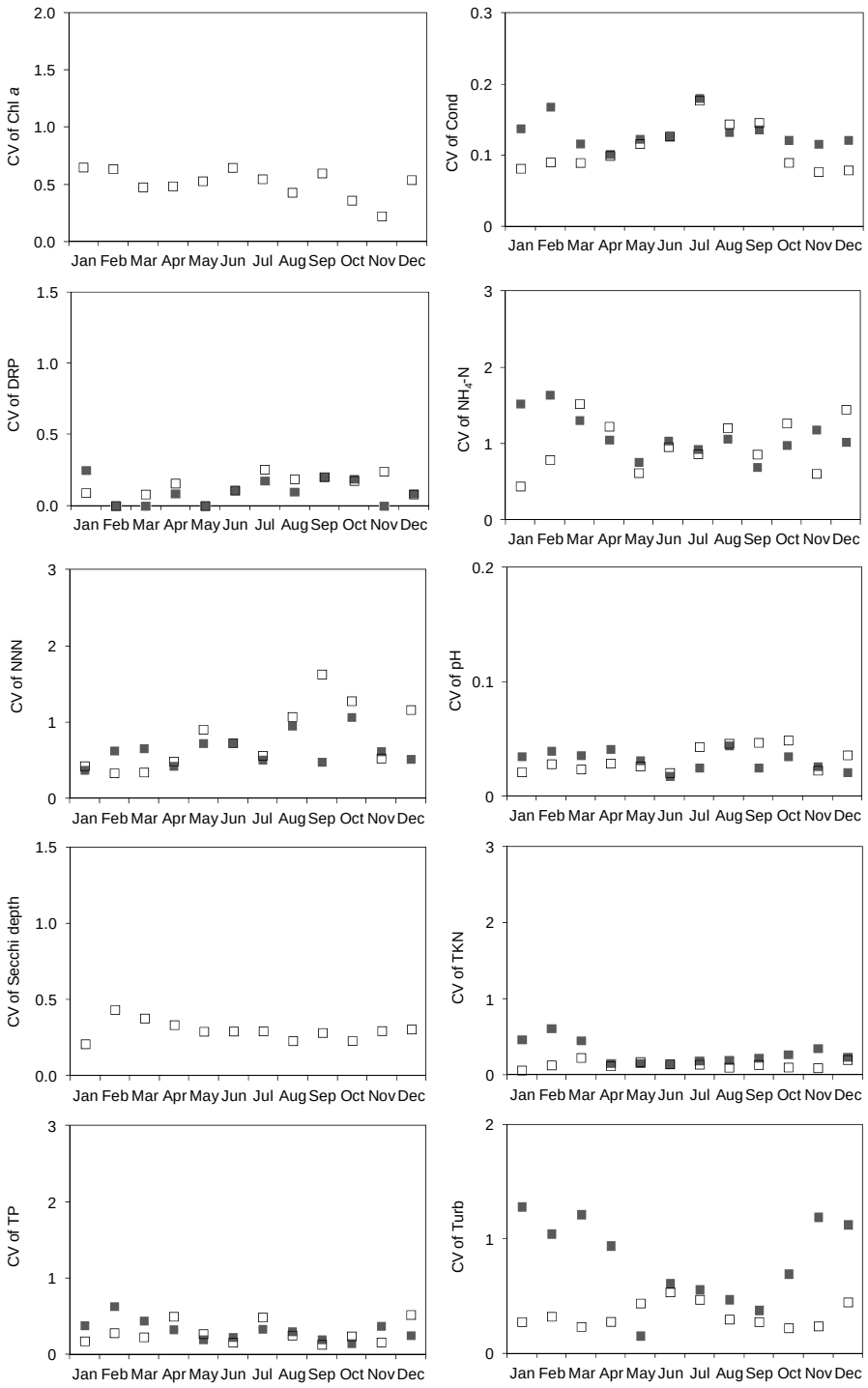
Appendix figure IV.1: Monthly CV values of different water quality variables for Lake Hakanoa. Empty squares are surface values and filled squares are bottom values.



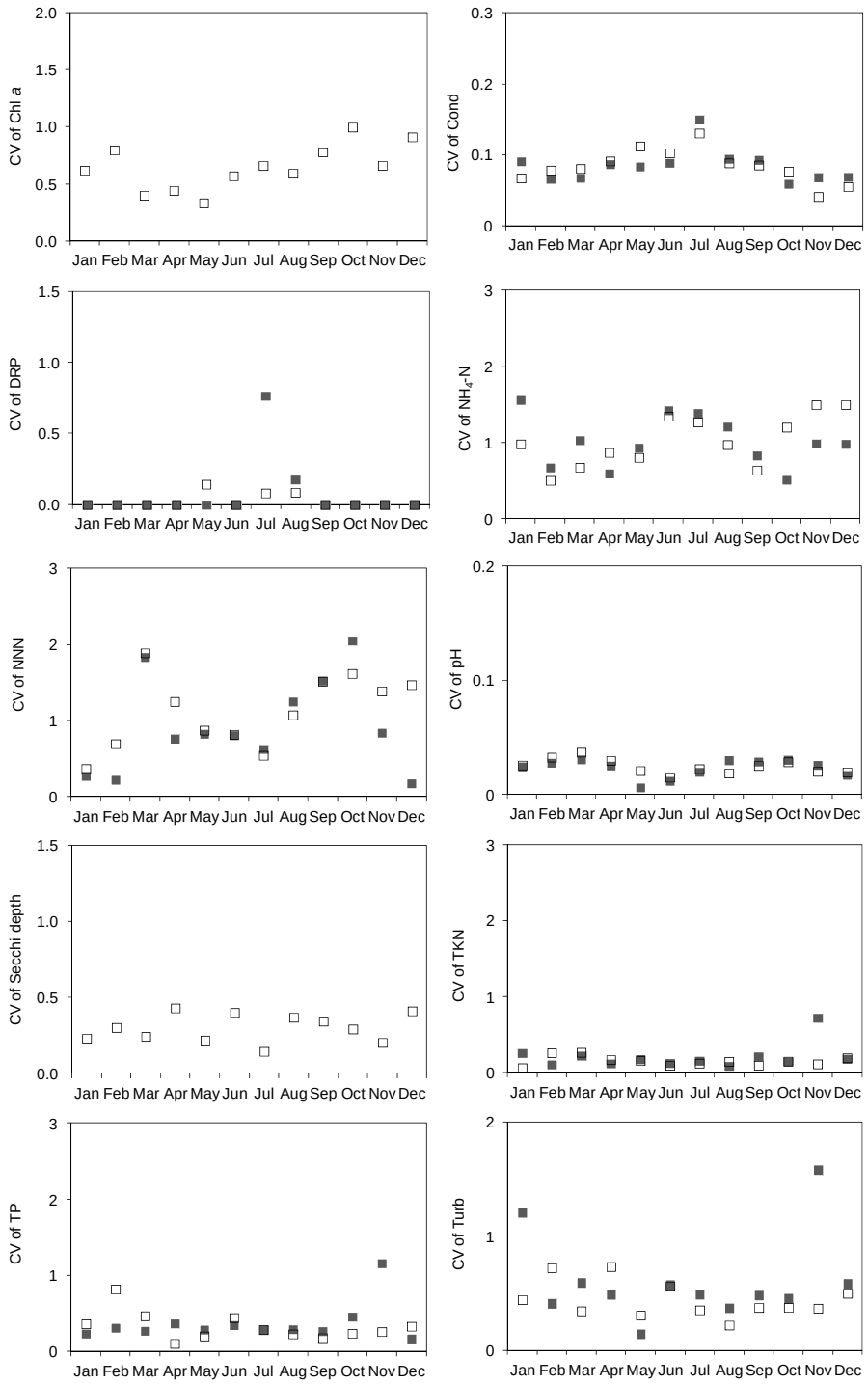
Appendix figure IV.2: Monthly CV values of different water quality variables for Lake Maratoto. Empty squares are surface values and filled squares are bottom values.



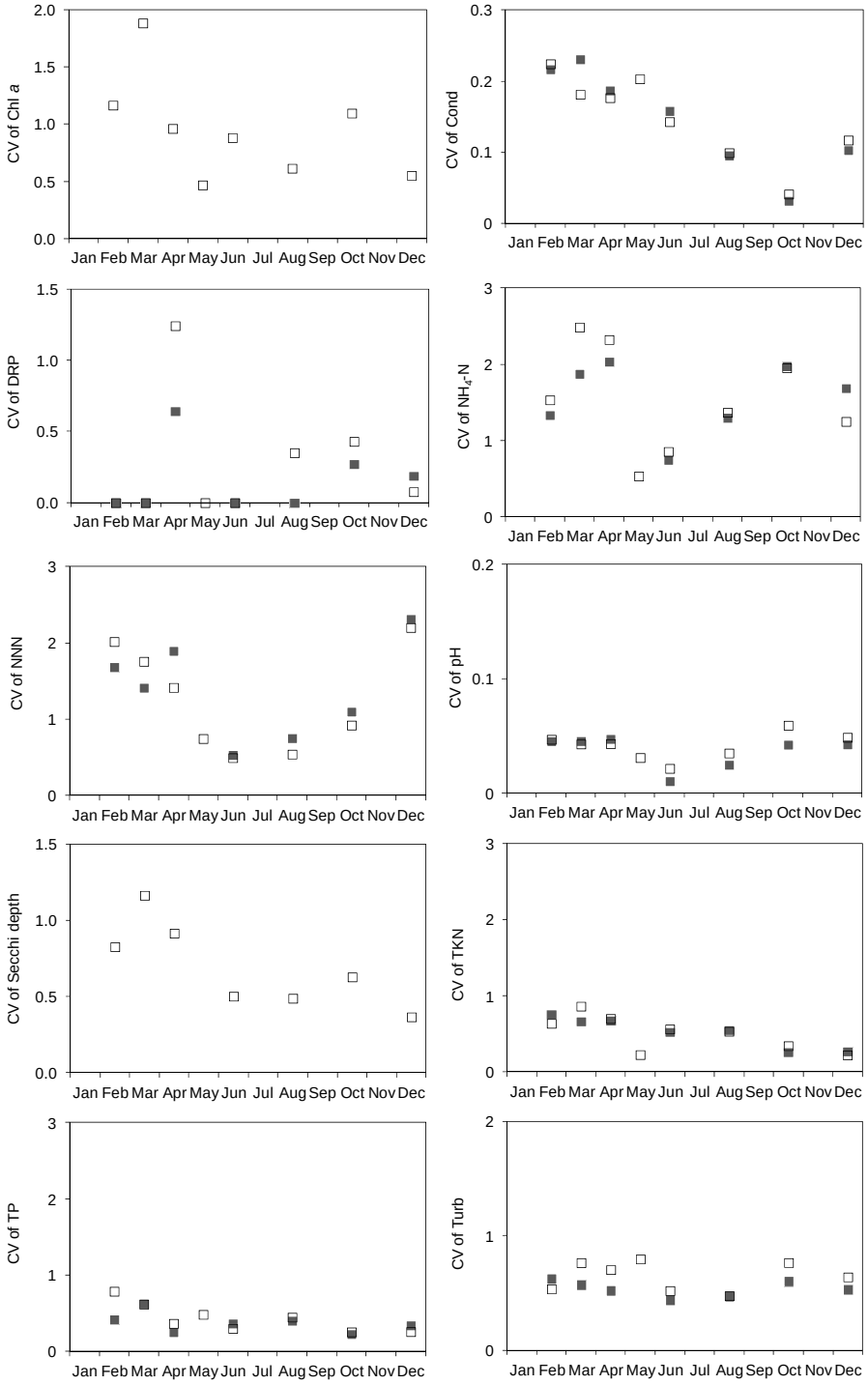
Appendix figure IV.3: Monthly CV values of different water quality variables for Lake Rotomanuka. Empty squares are surface values and filled squares are bottom values.



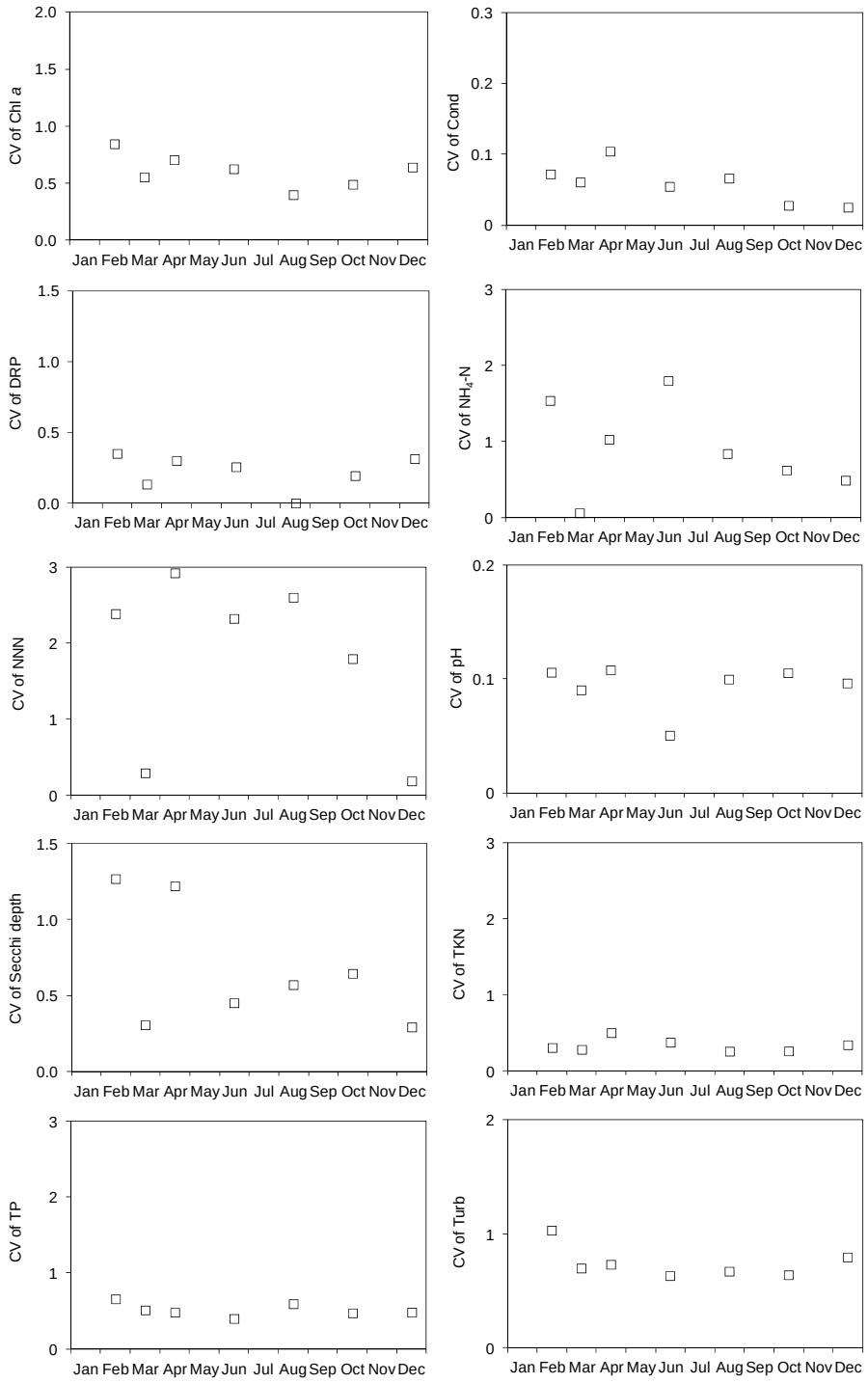
Appendix figure IV.4: Monthly CV values of different water quality variables for Lake Sepentine East. Empty squares are surface values and filled squares are bottom values.



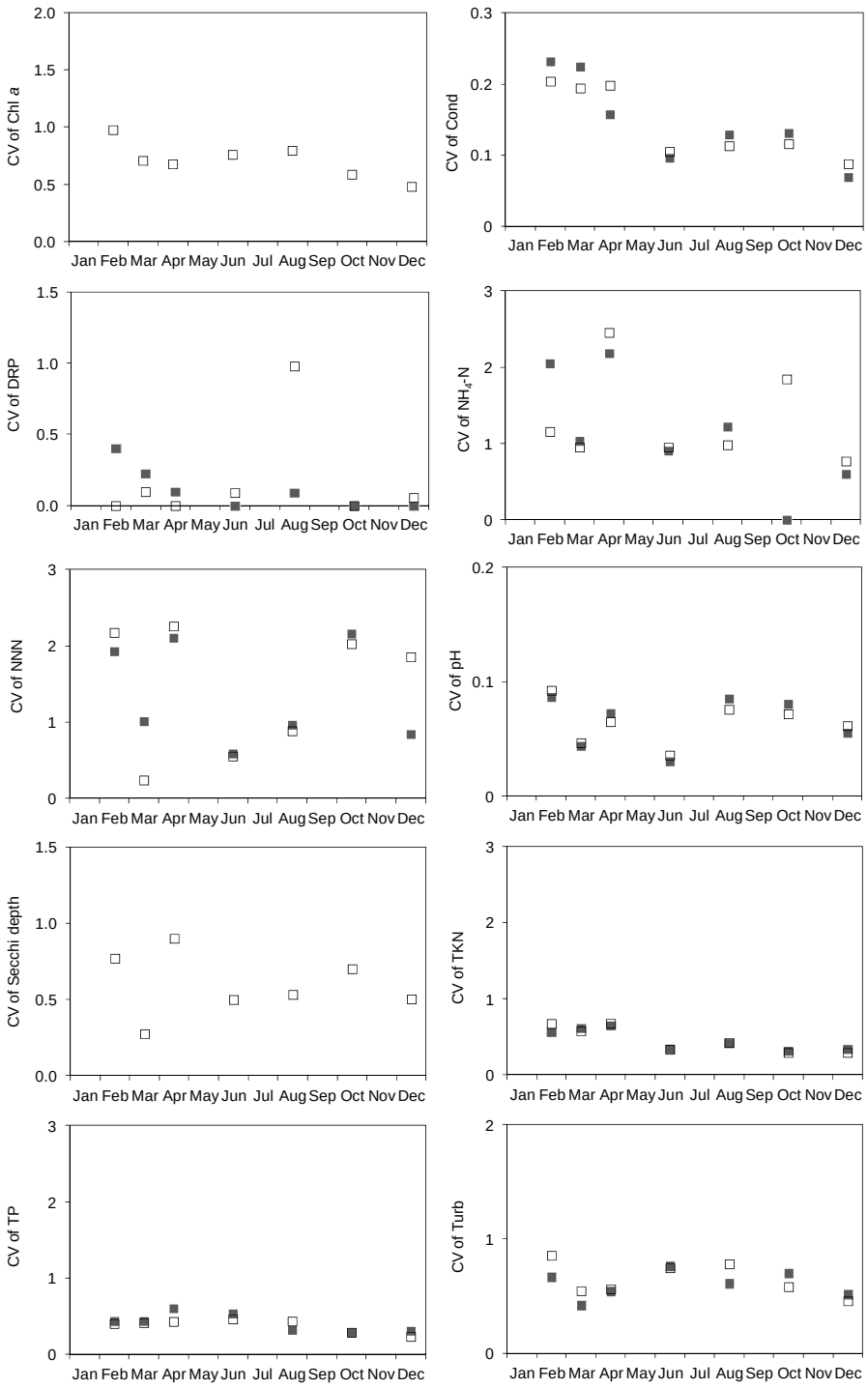
Appendix figure IV.5: Monthly CV values of different water quality variables for Lake Serpentine North. Empty squares are surface values and filled squares are bottom values.



Appendix figure IV.6: Monthly CV values of different water quality variables for Lake Waahi. Empty squares are surface values and filled squares are bottom values.

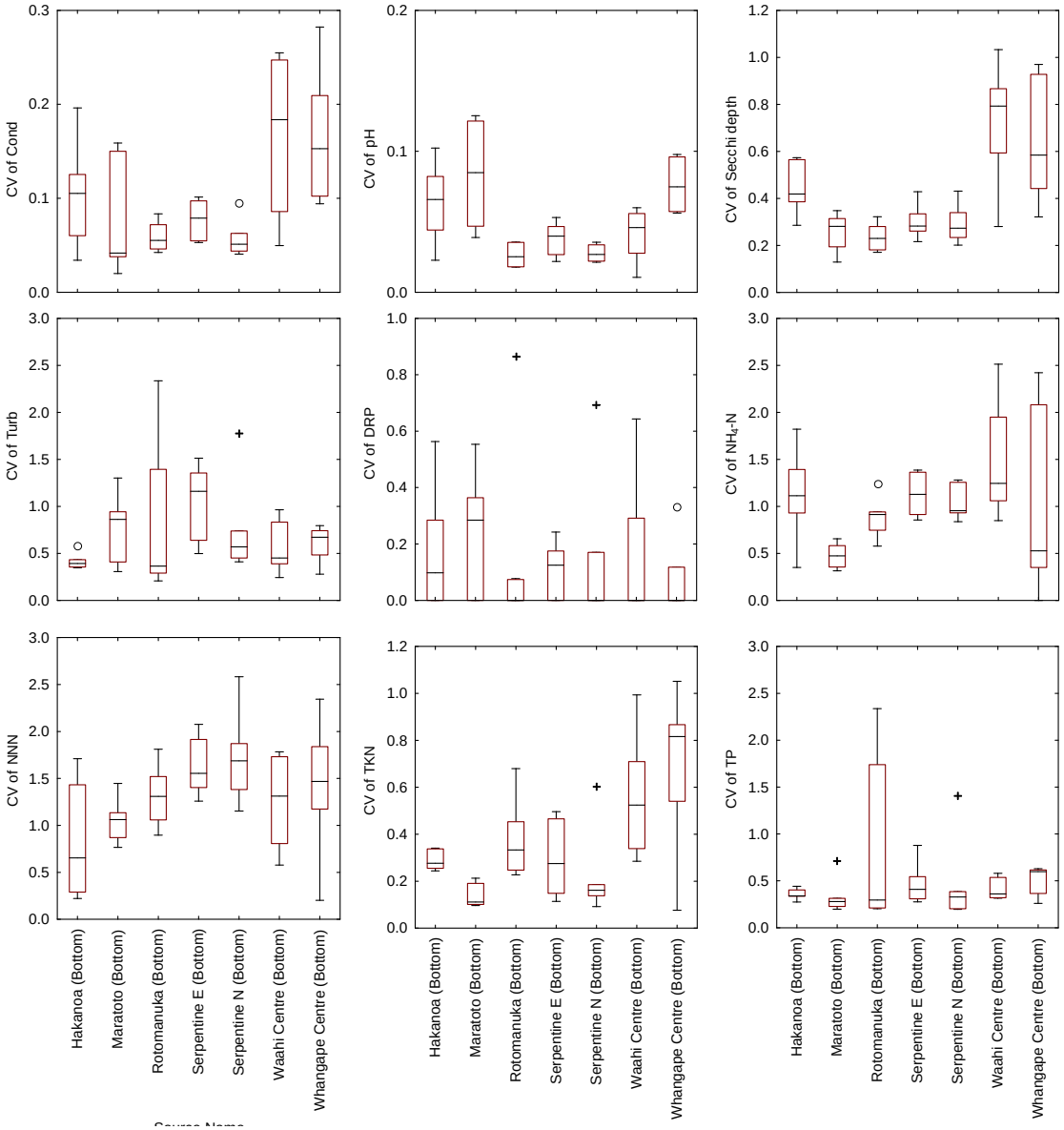


Appendix figure IV.7: Monthly CV values of different water quality variables for Lake Waikare. Empty squares are surface values and filled squares are bottom values.

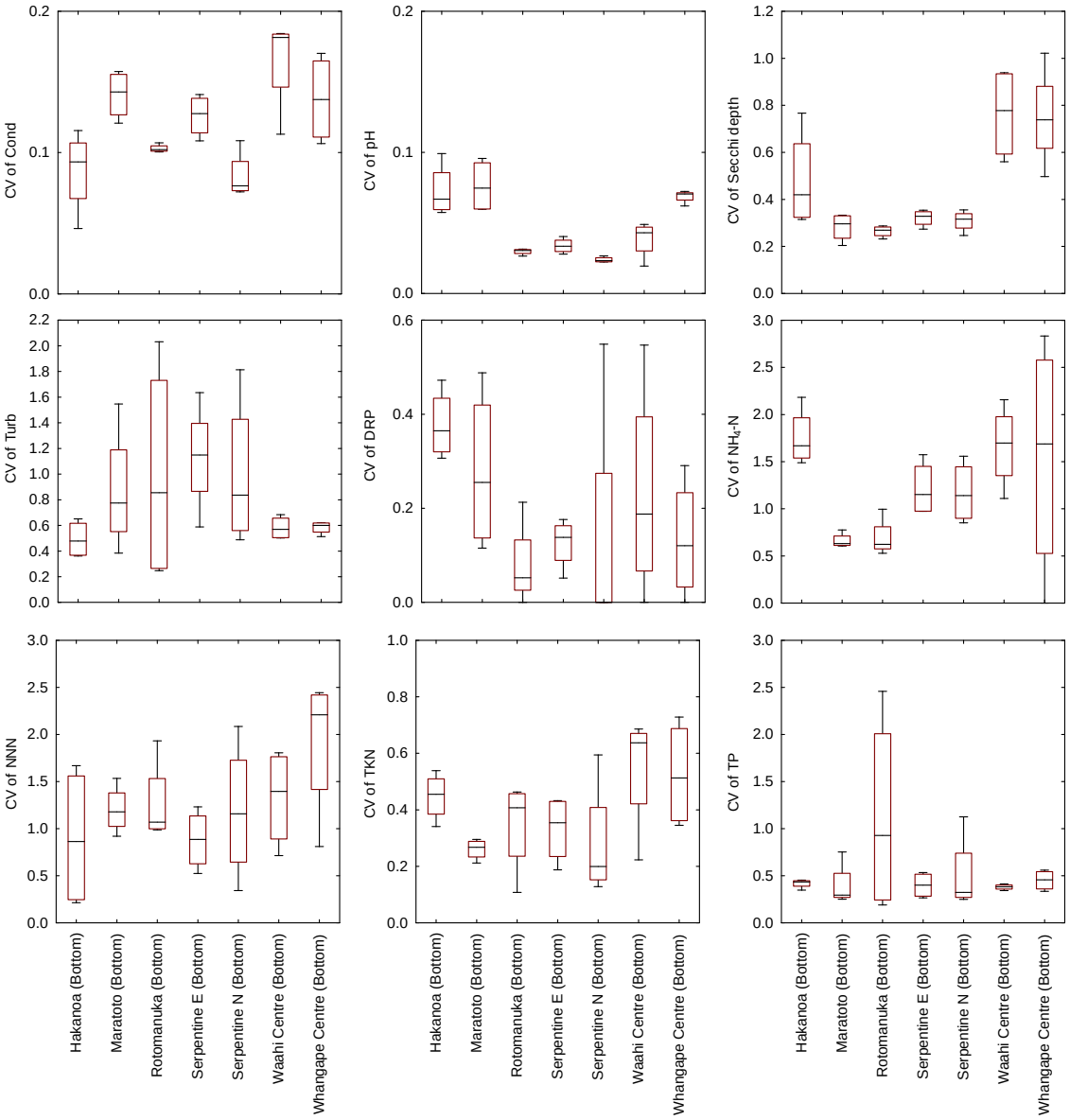


Appendix figure IV.8: Monthly CV values of different water quality variables for Lake Whangape. Empty squares are surface values and filled squares are bottom values.

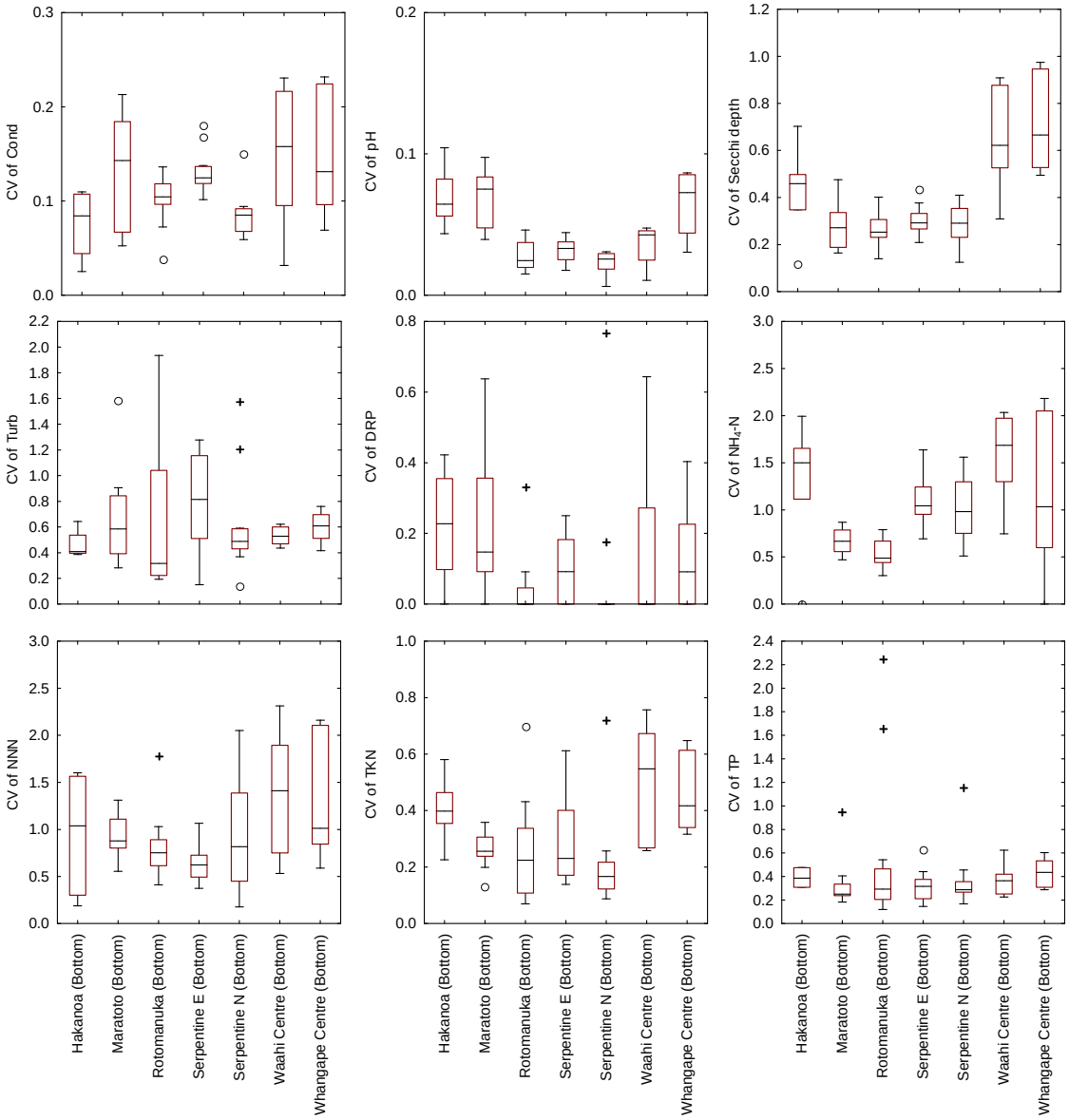
Appendix V: Compilations of CV values across different temporal scales



Appendix figure V.1: Compilation of median annual CV values for different water quality variables based on data from bottom measurements between 2002-2008 for eight Waikato lakes. Annual CV values were calculated from annual average values between 2002 and 2010. Lines represent the median value, boxes represent 25% and 75% percentile, whiskers represent the non-outlier range, circles represent outliers and asterisks represent extreme values.

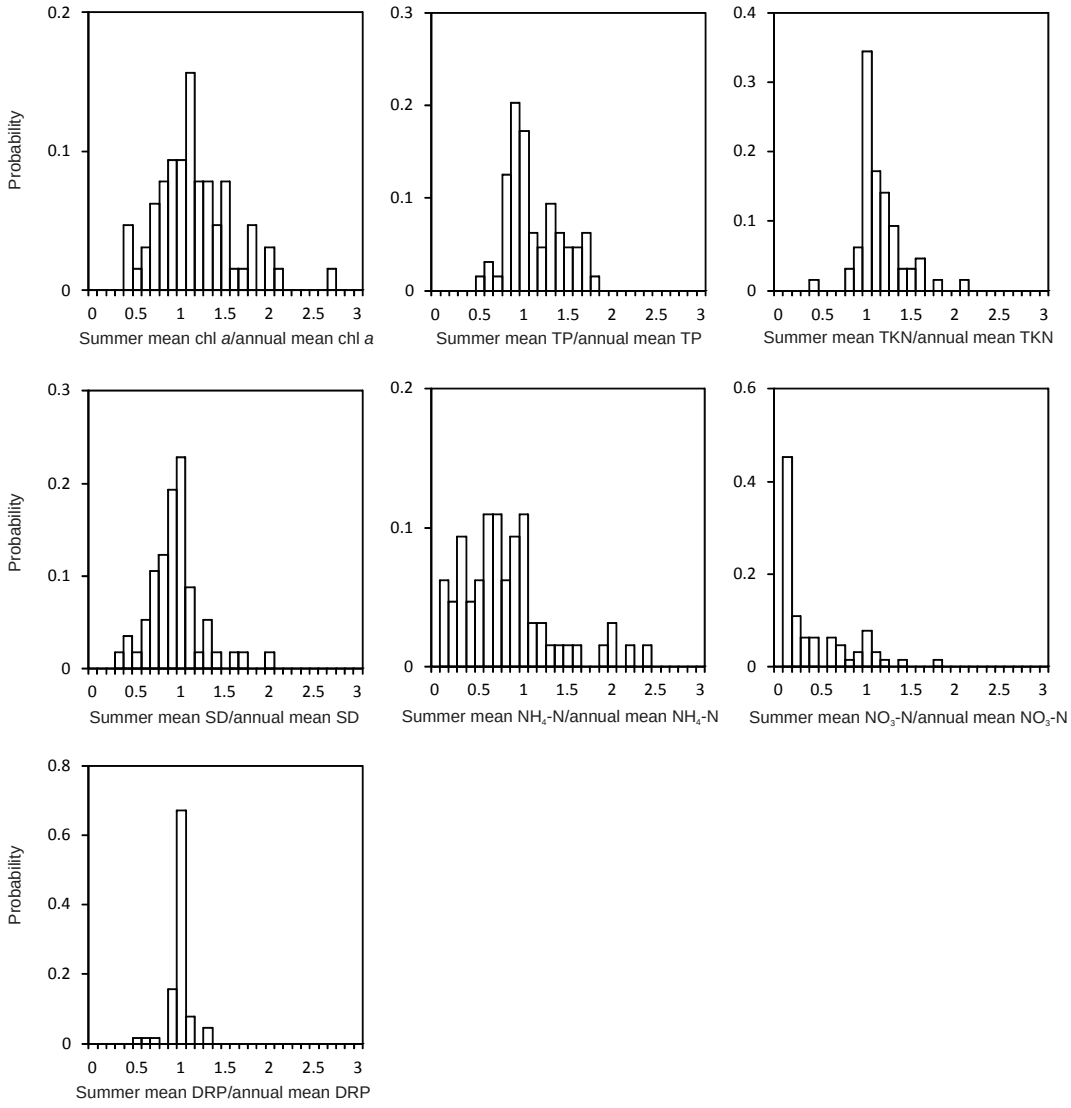


Appendix figure V.2: Compilation of median seasonal CV values for different water quality variables based on data from bottom measurements between 2002-2008 for eight Waikato lakes. Seasonal CV values were calculated from seasonal average values (i.e. summer, autumn, winter, spring) across several years. Lines represent the median value, boxes represent 25% and 75% percentile, whiskers represent the non-outlier range, circles represent outliers and asterisks represent extreme values.

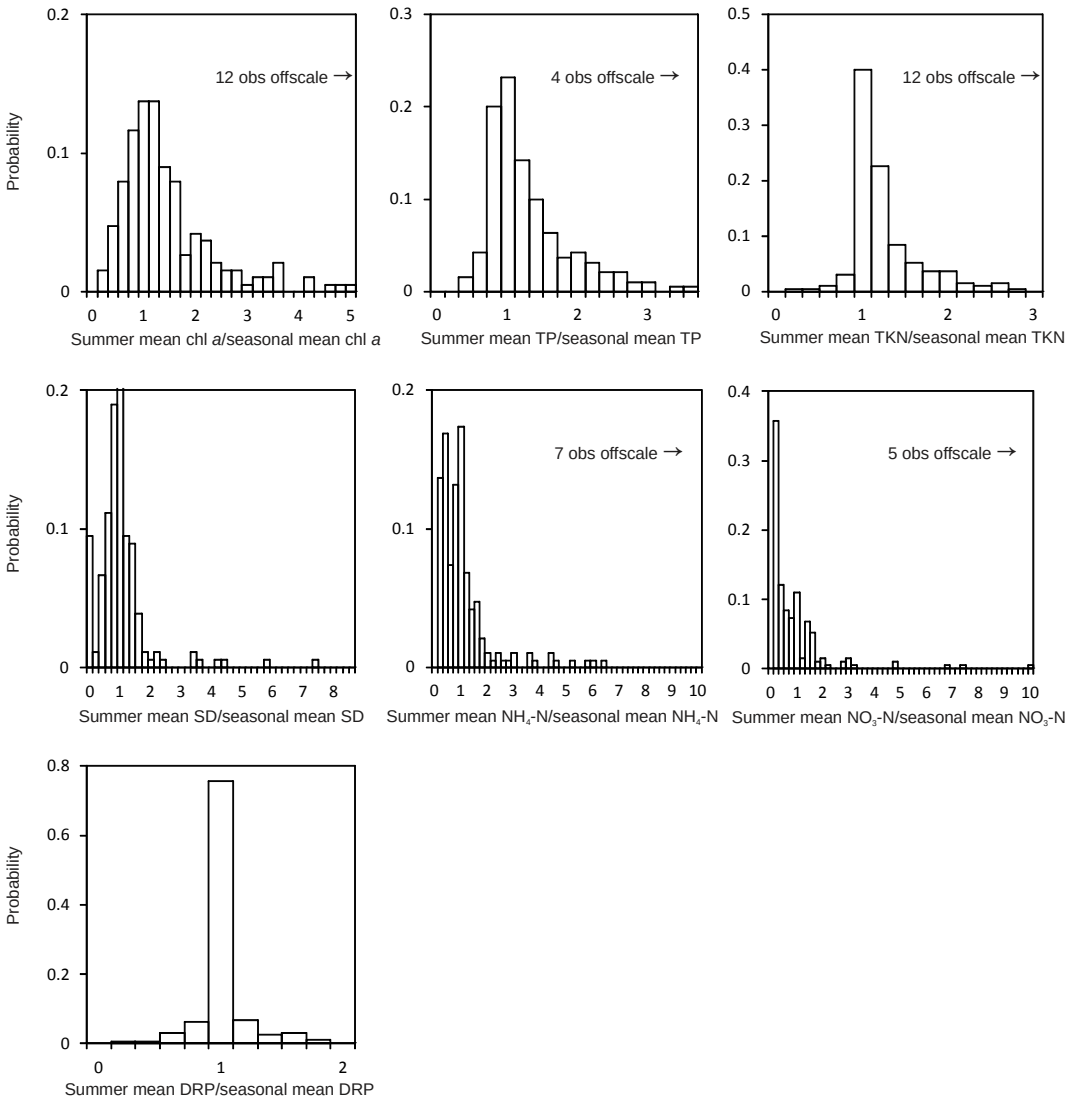


Appendix figure V.3: Compilation of median monthly CV values for different water quality variables based on data from bottom measurements between 2002-2008 for eight Waikato lakes. Monthly CV values were calculated from monthly average values (i.e. January until December) across several years. Lines represent the median value, boxes represent 25% and 75% percentile, whiskers represent the non-outlier range, circles represent outliers and asterisks represent extreme values.

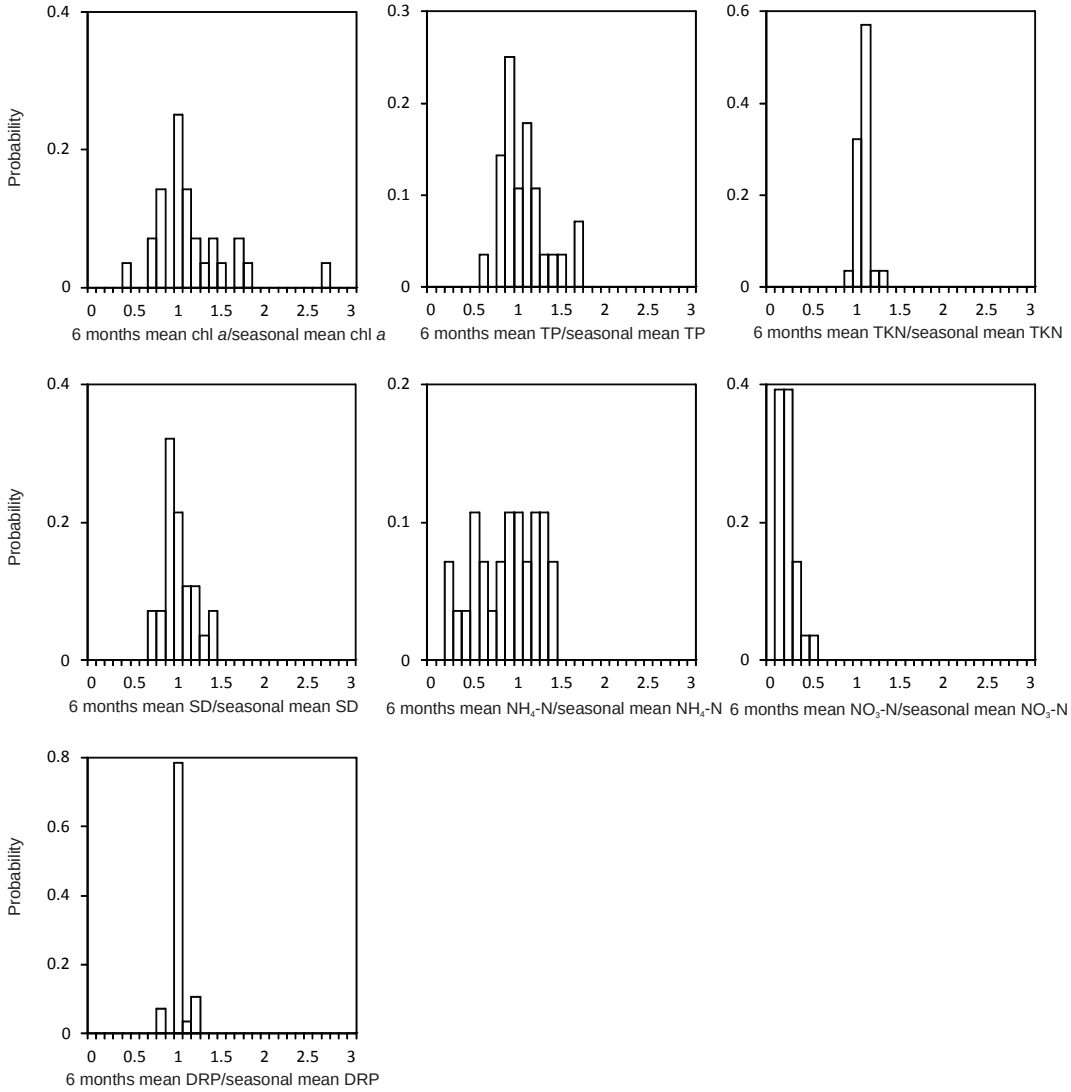
Appendix VI: Probability distributions for trophic state variables in 8 lakes



Appendix figure VI.1: Probability distribution for trophic state variables in eight shallow Waikato lakes of summer mean values/annual mean values.



Appendix figure VI.2: Probability distribution for trophic state variables in eight shallow Waikato lakes of summer mean values/seasonal mean values.



Appendix figure VI.3: Probability distribution for trophic state variables in eight shallow Waikato lakes of 6 months (i.e. December to May) mean values/seasonal mean values.