Lake water quality in New Zealand 2010: Status and trends

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Executive summary

This report provides a national picture of the current status (2005-2009) and long term trends of water quality in New Zealand lakes. The status is reported mainly in terms of recognised national indicators – the Trophic Level Index (TLI) and LakeSPI (Lake Submerged Plant Indicator). The results are discussed in the context of differences in lake types and land use and are extrapolated to estimate water quality for all lakes in New Zealand.

Lake water quality was assessed for 112 lakes for the period 2005-2009. There were a significant number of lakes for which Secchi depth data was not available. Excluding Secchi depth from the calculation of the TLI made little difference to overall scores; consequently trophic state was assessed using a modified version of the TLI calculated from total nitrogen (TN), total phosphorus (TP) and chlorophyll *a*.

Forty four percent (49/112) of currently monitored lakes were found to be eutrophic or worse (i.e., TLI >4), and 33% oligotrophic or better (i.e., TLI <3). The TLI score increased with increasing percentage pastoral land cover and decreased with increasing percentage native or alpine land cover.

The water quality results were extrapolated to all New Zealand lakes (>1 ha) using a regression tree analysis based on climate, lake morphology and land cover. This provided statistics that out of 3820 NZ lakes 32% would be eutrophic or worse (TLI >4), while 43% would be oligotrophic or better (TLI <3).

Ecological condition was assessed using LakeSPI for 155 lakes since 2005. Thirty-three percent of lakes had 'high' or 'excellent' ecological condition (i.e., LakeSPI score >50%); while 37% of lakes had poor ecological condition or were not vegetated with submerged plants (i.e., LakeSPI score <20%). In contrast half the lakes with pastoral land cover had poor ecological condition or were not vegetated.

Dissolved oxygen-temperature profiles were examined for 63 lakes. Eleven percent of lakes had mean bottom dissolved oxygen (DO) concentrations <3 mg/L. However, under stratified conditions (recorded in 46 lakes) 63% of the lakes had mean bottom water dissolved oxygen concentrations <3 mg/L. Hypoxic bottom water in these lakes likely enhances the release of phosphorus from lake sediments and may accelerate eutrophication.

Trends in TLI were analysed for 18 lakes over ten years since 2000. Three of these lakes (17%) had deteriorated significantly and one lake (6%) had improved significantly (Lake Omapere). Trends were analysed for 68 lakes for five years since 2005. The trend analysis found 19 lakes (28%) had deteriorated and eight lakes (12%) had improved. While there were more lakes that declined than lakes that improved, there was a slight but significant decrease in mean TLI (indicating improved condition) because the lakes that declined were on average oligotrophic while the improving lakes were on average eutrophic.

The status of NZ lake water quality was compared with a subset of lakes from Europe, USA and Canada. The comparison showed that median TN is lower in NZ lakes compared to lakes in Europe and USA and median TP concentration is similar in NZ lakes and European lakes. The median chlorophyll a concentration was slightly higher in European lakes (5.4 mg m^{-3}) than in NZ lakes (4.2 mg m^{-3}).

1. Introduction

In 2006 the Ministry for the Environment (MfE) commissioned two reports to provide a national snap-shot of lake water quality and lake water quality monitoring in New Zealand (Hamill 2006 and Sorrell 2006). MfE commissioned Opus International Consultants (Opus) and NIWA to update these reports, and in particular to:

a) provide a stocktake and report on current lake monitoring programmes;

b) assess at a national scale the status and trends in water quality of New Zealand lakes.

Understanding of current lake monitoring and reporting in New Zealand will assist the Ministry's Dependable Monitoring and Reporting Project in the *New Start for Fresh Water* programme. It is intended that this lake monitoring stock-take and lake condition state-trend analysis will contribute to improving the consistency of freshwater monitoring and reporting that was initiated though the National Environmental Reporting Forum in April and October 2009 (PCE 2010).

Hamill and Verburg (2010) describe current lake water quality monitoring and reporting programmes in New Zealand. Their report focuses on State of the Environment (SOE) monitoring programmes run by regional councils and does not cover one-off investigations or monitoring undertaken as part of public water supply investigations or special research investigations.

This report describes the current status (2005-2009) of lake water quality in New Zealand and long term trends. The status is reported mainly in terms of recognised national indicators – the trophic level index (TLI) and Lake Submerged Plant Indicators (LakeSPI). The results are analysed and interpreted in the context of differences in lake types[1] and land cover so as to allow results to be extrapolated to estimate water quality for all lakes in New Zealand.

The current report expands on Sorrell (2006) by:

1. reviewing dissolved oxygen-temperature profiles and bottom water oxygen concentrations (providing a first indication of the likelihood of internal nutrient release occurring in lakes as a result of hypolimnetic deoxygenation); and

[1] Derived from the Waters of National Importance (WONI) lake classification.

2. placing New Zealand lake water quality in an international context by providing a comparison of data relating to water quality between lakes in New Zealand, the USA, Canada and Europe.

The focus of this report is SOE monitoring undertaken by regional councils in the period elapsed since the first ‘snapshot’ reporting in 2006. In order to keep the current report concise, repeating findings discussed in the previous snapshot reports has been avoided (Hamill 2006 and Sorrell 2006).

2. Lake water quality status

2.1 Methods

A detailed description of the data analysis methods used in this report is given in Sorrell (2006).

Raw data sets

The lake water quality data set used for this study was based on the data set compiled for the 2006 snapshot of lakes water quality (Sorrell 2006), supplemented with more recent data (to December 2009) forwarded by regional councils in response to a request from MfE in April 2010. In all cases where the more recent data set overlapped with the existing data, the existing records were deleted and replaced with the new data, so as to ensure the subsequent analyses were based on the most currently supplied data. The resulting data set represented 154 lakes, in 14 regions, for which there were at least some water quality data available. Just under half of these data (45% of all records) were for the period 2005-2009, with most of the remainder (52% of the total) covering the period 1990-2004. We then applied the following criteria to extract a subset of data suitable for the present study:

- for any given lake, at least some data were available for the period 2005-2009. Lakes for which no data had been collected since January 2005 were not considered further;
- for the lakes selected, data from before 1990 or more recent than 2009 were discarded;
- sampling sites such as shallow bays which we considered atypical of the lake as a whole, or were not representative of surface water (nominally the top 10 m), were discarded.

After applying these criteria the final working data set represented 119 lakes with varying amounts of data from 2005 to 2009 (112 lakes with TN, TP and chlorophyll a), and possibly additional data as far back as 1990. Most lakes were represented by a single sampling site, with the exception of Lake Omapere (NRC; two sites), Lake Wairarapa (GWRC; four sites), Lake Pearson (ECAN; two sites), Lake Manapouri (ES; three sites) and Lake Te Anau (ES; two sites). A further two lakes (Lake Rotoiti and Lake Rotomahana (BOP)) were represented by a single site in any one year, but by two different sites over the full (1990-2009) period of record.

Nutrient concentrations below detection limits were replaced before calculations with values equal to half the detection limit. Dominant land cover was determined as the land cover type (mapped from LCDB2) with the largest percentage cover following Sorrell (2006). However, we recognise that minority areas of land cover can sometimes dominate as sources of contaminants, notably nutrients, affecting lake condition. Therefore, lake water quality is examined relative to the percentage of different types of land cover.

Data analysis

We calculated means for each sampling day for all variables of interest in the epilimnion in each lake, averaging across multiple sites per lake as necessary. These means were the basis for all subsequent analyses. We restricted the analysis to variables with at least six measurements during the period 2005-2009.

Trophic state

The TLI (Burns et al., 2000) was calculated in two ways (following Sorrell 2006), as TLI4 (using TN, TP, Chlorophyll *a* and Secchi data) and as TLI3 (without using Secchi disk data). There were 112 lakes for which TLI3 could be calculated while 70 lakes had data suitable for calculation of TLI4. TLI3 did not differ significantly from TLI4 ($R^2 = 0.98$, linear regression TLI4 = 0.99TLI3 + 0.03, df = 69, $p < 0.00001$, Fig. 1), which suggests appreciable redundancy (i.e., cross-correlation) between Secchi and TN, TP and Chlorophyll *a* data. There are a number of lakes for which there is no Secchi depth data, therefore we consider mainly TLI3 results in this report. The classes used for reporting trophic state results are as in Sorrell (2006).

Ecological condition

LakeSPI (expressed as a percentage) is an index of ecological condition based on key features of macrophyte community structure and composition (Clayton and Edwards 2006a, b; Hamill 2006; Sorrell 2006). The classes of ecological condition used for reporting LakeSPI results were:

> 75 %	"Excellent"
>50-75 %	"High"
>20-50 %	"Moderate"
>0-20 %	"Poor"
0	"Non-vegetated" (defined as having a macrophyte cover of <10%)

These class boundaries are consistent with those now commonly used for reporting LakeSPI (Mary De Winton, personal communication) but are slightly different from the class boundaries used in Hamill (2006)[2]. In total, 155 lakes were assessed for LakeSPI since 2005.

Dissolved oxygen in bottom waters

Where dissolved oxygen profiles were available, they were analysed by recording the temperature and dissolved oxygen concentrations for the bottom and top of the water column, as well as depth. Lakes were defined as stratified if the difference between the top and the bottom of the profile was greater than 3 ^{o}C.

A total of 3964 oxygen depth profiles were collated for 63 lakes since 1981 (1821 data points were available in 2005-2009). The number of measurements per lake varied from 1 to 767.

Extrapolation to all lakes in New Zealand

Sorrell (2006) used regression tree analysis to relate water quality variables (TN, TP and chlorophyll *a* concentrations) to climate, lake morphology and land cover variables. This resulted in seven groupings of lakes which differed in TN, TP and chlorophyll *a* concentrations and which varied from oligotrophic (group 1, TLI < 3) to hypertrophic (group 7, TLI > 6). We use here the same tree constructed by Sorrell (2006) and the classes defined by climate, lake morphology and land cover variables to extrapolate our findings of trophic state (in terms of the TLI) to all 3820 lakes in New Zealand larger than 1 ha.

2.2 Results and discussion

Monitoring

The monitored lakes account for about 3% of all lakes in New Zealand larger than 1 ha (3820 lakes). For the distribution of maximum depth, altitude and lake area among monitored lakes, and a comparison with all lakes in New Zealand, see Hamill and Verburg (2010). The total number of lakes sampled in any one year as part of the long term monitoring program has increased from 27 in 1990 to 117 in 2008 (Fig. 2). The average number of variables that were measured in each lake ranged between 10 and 12 since 2000 (Fig. 2). There were 112 lakes for which TN, TP and chlorophyll *a* concentration data were available for analysis and reporting of TLI for the period 2005-2009. This was slightly less than in Sorrell (2006; 121 lakes). However, the number of lakes in the 2006 analysis included all lakes for which data were available irrespective of when they were collected, and therefore included lakes which had not been monitored in recent years (Sorrell 2006). In the current analysis more lakes had sufficient data available for a trend analysis of TLI (68 lakes) than in 2006 (49 lakes).

[2] In Hamill (2006) the boundary between Excellent and High was 85% compared to 75% now used, and the class of non-vegetated lakes was not considered separately.

Trophic state

Between 2005 and 2009 the largest percentage of lakes (27%) was in the mesotrophic range (Table 1). Microtrophic and oligotrophic lakes were concentrated in Canterbury and seven out of a total of eleven hypertrophic lakes were in Canterbury and Waikato. Glacial lakes were typically microtrophic to oligotrophic while riverine lakes were typically supertrophic to hypertrophic (Table 2). Of monitored lakes in catchments dominated by pastoral land cover 84% were mesotrophic to hypertrophic, while lakes with dominant native land cover were typically oligotrophic (Table 3). These patterns are generally consistent with known patterns in pastoral nutrient enrichment (e.g., Davies-Colley 2009) which drives lakes to higher trophic levels. While we present TLI data in relation to dominant land cover type as was done by Sorrell (2006), we note that dominance of one type of land cover, for instance native land cover, does not preclude potential (changes in) effects from pastoral sections of the same catchments.

The TN and TP concentrations were significantly higher in shallow lakes (<10 m deep; average TN = 1087 mg/m^3, average TP = 78 mg/m^3) than in deep lakes (>10 m deep; average TN = 309 mg/m^3, average TP = 18 mg/m^3; *t*-test, t > 5.13, df = 117, p <0.00001 both for TN and TP concentrations). The correlation between TN and TP concentrations (Fig. 3) was high (R = 0.86). The mass ratio of TN to TP tended to be higher in the shallow lakes but the difference was not significant (averaged 25 in lakes <10 m deep and 20 in lakes >10 m deep). TN:TP was significantly lower in the more eutrophic lakes (average TN:TP = 29 for lakes with TP <20 mg/m^3, and 17 for lakes with TP >20 mg/m^3; *t*-test, t = 3.94, df = 117, p <0.0005).

TLI3 correlated well with percentage pastoral (R = +0.52, p < 0.00001), alpine (R = -0.55, p < 0.00001), and native (R = -0.53, p < 0.00001) land cover types (Fig. 4), while there was no significant correlation between percentage urban (R = +0.14, p > 0.05) or exotic (R = +0.12, p > 0.05) land cover and TLI3. TLI3 increased with increasing percentage pastoral land cover and decreased with increasing percentage native or alpine land cover (Fig. 4). A ranking of all monitored lakes shows that average TLI3 is almost evenly distributed among the lakes (Fig. 5). The most pristine lakes are Coleridge, Tekapo and Benmore (average TLI3 = 1.3 for each lake in 2005-2009), and the most impacted lakes are Ellesmere, Rotorua-Canterbury, and Waikare (average TLI3 = 6.9 for each lake in 2005-2009).

Median TLI3 was highest in lakes with predominantly pastoral land cover and, unsurprisingly, lowest in lakes with alpine land cover (Fig. 6). Nutrient enrichment from pastoral land use is also a clear pattern in river water quality (Ballantine and Davies-Colley 2009; Ballantine et al., 2010). Median TLI3 was highest in riverine lakes and lagoons, and lowest in glacial lakes (Fig. 7), consistent with the high percentage of alpine land cover in catchments of glacial lakes. Mean TLI3 was higher in North Island lakes (TLI3 = 4.3, n = 64) than in South Island lakes (TLI3 = 3.4, n =

48; means and medians were identical). Median TLI3 was highest in Waikato and the Manawatu-Wanganui region (the latter represented by only one lake, Lake Horowhenua, with a TLI3 of 6.3) and lowest in Canterbury and Southland lakes (Fig. 8). This regional trend is related to the Waikato lakes being mostly shallow, river floodplain lakes subjected to nutrient enrichment from pastoral land, while near-pristine alpine lakes are concentrated in Canterbury, Otago and Southland. Variability in TLI was largest among Otago lakes.

The individual variables contributing to the TLI, TN, TP and chlorophyll *a* concentrations, show the same trends between land cover classes as TLI (Table 4), with highest values in the pasture class and lowest in the alpine class, while Secchi disk depth shows the opposite pattern.

LakeSPI (Submerged Plant Index)

The median LakeSPI was lowest in lakes with dominant pastoral land cover and highest in lakes with dominant alpine (only one lake examined) and exotic (n = 25) land cover (Fig. 9). While we present LakeSPI data in relation to dominant land cover type, we note that dominance of one type of land cover, for instance native land cover, does not preclude potential (changes in) effects from pastoral sections of the same catchments.

Peat lakes include three lakes that are in the range of high or excellent ecological condition (50-100%) while LakeSPI was 0% in all other peat lakes for which this index has been reported, meaning <10% macrophyte vegetation (Fig. 10). Median LakeSPI in peat lakes was therefore zero (and in riverine lakes as well), while it was highest in dune lakes (Fig. 10). Median LakeSPI was similar in dune and glacial lakes. Median LakeSPI was highest in Southland, closely followed by Northland, Canterbury and Otago, and it was zero in Waikato (Fig. 11). The greatest number of LakeSPI results per region were collected in Waikato (n = 49) with only two observations from West Coast and Otago.

Percentage LakeSPI correlated well with the percentage of the catchment with pastoral ($R = -0.51$, $p < 0.00001$), alpine ($R = +0.33$, $p < 0.005$), and native ($R = +0.32$, $p < 0.005$) land cover types (Fig. 12), while there was no significant correlation between percentage urban ($R = -0.04$, $p > 0.05$) or exotic ($R = -0.20$, $p > 0.05$) land cover and TLI3. LakeSPI decreased with increasing percentage pastoral land cover and increased with increasing percentage native or alpine land cover (Fig. 12). Therefore, the relationships of lake condition with percentage of the various types of land cover were the same whether TLI3 or LakeSPI was used as the indicator variable, and the strength of the correlations were similar, in particular for percentage pasture.

Linear correlation between LakeSPI and TLI was only moderate ($R = 0.54$, $n = 78$, $p < 0.00001$). LakeSPI and trophic status of lakes are correlated but rather weakly because they are indicators of rather different aspects of overall lake condition. LakeSPI is a variable that is partly related to water quality, for instance by accounting for the maximum depth of macrophyte growth, which relates to water clarity (Vant et al., 1986), but additionally includes information on the presence and abundance of invasive macrophytes which negatively influence LakeSPI (Clayton 2006). Therefore, LakeSPI and TLI are not expected to correlate strongly; they are indexes that inform us of somewhat different aspects of the ecological integrity of lakes. The 'moderate' category (20-50% LakeSPI) included the greatest number of lakes (30% of lakes; Table 5). In Northland many of the lakes were in excellent condition (35% of lakes). Partly because a large fraction of the lakes that were sampled for LakeSPI were in Northland (24%), these lakes accounted for 57% of all lakes with excellent condition (Table 5). Most of the lakes in Waikato (51%) were non-vegetated, having a macrophyte cover of <10% (Table 5). Of all lakes 23% were non-vegetated, 69% of which were in Waikato. Many lakes in the LakeSPI classification were dune lakes (37% of those where lake type was determined), which tended to be higher in ecological condition than other lake types (Table 6). Half of the lakes with pastoral land cover (50%) were in poor ecological condition or were non-vegetated (Table 7), while lakes with native and exotic cover typically had excellent to moderate ecological condition (Table 7). The relationship of LakeSPI scores with land cover may relate partly to nutrient enrichment and other pollutant stressors (notably fine sediment) from pasture, and human activities as a vector for invasive aquatic weed transfer.

Extrapolation

Water quality results were extrapolated to all New Zealand lakes (>1 ha) using the regression tree of Sorrell (2006). This showed that the mean TLI of all lakes (with the means of the seven regression groups weighted by the number of lakes in those groups) was 3.4, i.e., in the mesotrophic range (Table 8). That is, NZ lakes are mesotrophic on average with a range from typical microtrophic in alpine areas through to typical hypertrophic in lowland lakes with intensive pastoral farming. Of 3820 NZ lakes greater than 1 ha 32% are predicted to be eutrophic to hypertrophic (TLI > 4, Table 8), while 43 % would be in the oligotrophic to microtrophic category (TLI < 3).

The lake grouping with the lowest median TLI (i.e., TLI 2.3, group 1 (very cold climates, Table 8) representing 43% of all lakes) had the highest median LakeSPI (57%); while the lake grouping with the highest median TLI (i.e., TLI 6.2, group 7 representing 1% of all lakes) had the lowest median LakeSPI (0%).[3]

[3] We decided not to extrapolate LakeSPI to a nationwide weighted mean value because LakeSPI records had not been taken into account in the determination of the seven water quality groups by the regression tree analysis of Sorrell (2006). Because LakeSPI results are not necessarily related to trophic state, it was not considered meaningful to sort LakeSPI scores

Dissolved oxygen in bottom waters

Low concentrations of dissolved oxygen in lake bottom waters can accelerate the flux of nutrients from lake sediments and result in a positive feedback contribution to eutrophication. Dissolved oxygen was assessed to identify lakes where this positive feedback may be occurring.

Dissolved oxygen–temperature profiles were available for 63 lakes. The average concentration of dissolved oxygen in the bottom water was 5.9 mg/l and 11% of the lakes had mean bottom dissolved oxygen concentrations less than 3 mg/l (Table 9). The lakes where the average oxygen concentration in bottom water was less than 3 mg/L were (in order of declining hypolimnetic oxygen depletion): Pupuke, Rotorangi, Waikopiro, Kuwakatai, Wainamu, Okaro, and Ototoa (Table 9). A large proportion of measurements of bottom water oxygen concentrations were less than 1 mg/L, and this proportion varied from about 10% to more than 20% between the periods of 1981-1999, 2000-2004 and 2005-2009 (Fig. 13). While half of the nearly 4000 measurements were collected in the period 1981-2004, these measurements were collected in far fewer lakes (21 lakes) than in the period 2005-2009 (63 lakes). No data were available before 2005 for six of the eight most oxygen-depleted lakes. Because most lakes are represented by the data set of 2005-2009 and many of the lakes with more depleted bottom waters were not sampled prior to 2005 a comparison for trends since 1981 is not useful and only data of 2005-2009 is presented in Table 9.

Temperature differences between surface and bottom water were least in June-August and largest in January-February (Fig. 14). Oxygen concentrations in bottom water were least in January-February and highest in June-August (Fig. 15).

Stratified conditions occurred in 46 of the 63 lakes and in 33% of the visits. The frequency of occurrence of stratified conditions per year will be slightly overestimated because there was a slight bias to summer time measurements, with 29% of measurements in January-March and 24% in June-August. The percentage of lakes where average bottom oxygen was <3 mg/L was much higher for lakes under stratified conditions (63%) than for lakes under non-stratified conditions (3.2%; Table 9). When stratified, the average concentration of dissolved oxygen in the bottom water was 2.9 mg/L. When not stratified, the average concentration of dissolved oxygen in the bottom water was 7.3 mg/L. Non-stratified conditions occurred in all 63 lakes sampled and in 67% of all site visits.

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by the same groupings as determined for TLI, or to extrapolate LakeSPI to all NZ lakes (personal communication Mary De Winton).

There were 30 lakes with more than 20 measurements. These lakes, and the few lakes with long time series such as Lake Rotorua, may merit a closer examination. However, this report is aimed at a nationwide comparison.

There was a small but significant positive correlation between bottom oxygen concentration under stratified conditions and site depth (R^2 = 0.17, n = 602, since 2005, and R^2 = 0.19, n = 1177, for all data, $P < 0.00001$). There was no significant relationship under non-stratified conditions. The correlation was slightly better between the mean bottom oxygen concentrations for each lake under stratified conditions and the maximum depth of the lake (R^2 = 0.24, n = 47, $P < 0.0005$, for all data). Higher bottom oxygen concentrations in deep lakes may seem counter-intuitive at first, because in deep lakes such as Pupuke (57 m) it is more difficult for oxygen to be mixed all the way down to the bottom. However, many deep lakes in NZ are oligotrophic, such that little organic matter is produced to drive oxygen consumption in bottom waters. Furthermore, these deep lakes typically overturn fully in winter with reoxygenation of the water column, thereby supplying a large amount of dissolved oxygen to the lake which is not much depleted on decomposition of the relatively small amount of organic matter produced by annual primary production.

Under non-stratified conditions the bottom and surface temperatures were on average 14.8 and 15.5 °C respectively across all 63 lakes in 1981-2009 (14.7 and 15.5 °C respectively in 2005-2009). Under stratified conditions the bottom and surface temperatures were on average 12.6 and 19.2 °C respectively in 1981-2009 (12.9 and 19.7 °C respectively in 2005-2009). The strength of stratification in the monitored lakes increased over the past few decades. The strength and duration of stratification in lakes increases as a result of climate warming with surface waters warming faster than bottom waters (Winder and Schindler 2004; Verburg and Hecky 2009). Vertical mixing, allowing deep circulation in a lake, is important to maintain oxygenated bottom waters. Climate warming reduces the replenishment of oxygen in bottom waters by reducing vertical mixing (Verburg et al., 2003). Therefore, it is to be expected that global warming will result in New Zealand lakes suffering increasing frequency and duration of bottom water anoxia, as has been found elsewhere (Adrian et al., 2009). Increased hypolimnetic anoxia resulting from climate warming has been shown to increase vulnerability of lakes to eutrophication (Adrian et al., 2009) by enhancing internal loading of nutrients from the sediments. The burial efficiency of phosphorus decreases with decreasing oxygen concentrations and under anoxic conditions, instead of net burial, phosphorus is released from the sediment to the water column (Vant 1987; Nurnberg 1984). The internal loading of phosphorus is expected to become progressively more important than external nutrient loading in fuelling eutrophication when hypolimnetic oxygen concentrations decline towards anoxia (Nurnberg 1984). Furthermore, increased runoff and external nutrient loading can compound such problems by increasing productivity with resulting increased oxygen consumption in bottom waters.

Evidence that high productivity in New Zealand lakes results in low bottom water oxygen concentrations, potentially resulting in enhancement of internal nutrient loading and further reduction in water quality, is provided by Figure 16. While there was no significant correlation between average or minimum bottom water oxygen concentrations and TLI, lakes with high average bottom water oxygen concentrations and high TLI included shallow and well mixed lakes such as Waikare and Whangape where resuspension of bottom sediment with nutrients during wind events probably contributes to the low water quality while the wind mixing ensures a well oxygenated water column. Separating the lakes by depth, in lakes >10 m deep bottom water oxygen concentrations decreased significantly (R = 0.52, ANOVA, df = 28, $p < 0.005$ in stratified lakes and R = 0.34, ANOVA, df = 33, $p < 0.05$ in stratified and non-stratified lakes) with increasing TLI (Fig. 16), while there was no relation between average bottom water oxygen concentrations and maximum bottom depth ($p > 0.05$). Bottom water oxygen concentrations decreased significantly (R = 0.41, ANOVA, df = 29, $p < 0.05$) with increasing percentage pastoral cover in lakes >10 m deep (excluding Lake Pupuke which has 40% urban cover and no pastoral cover). This suggests that external nutrient loading resulting in enhanced productivity and increased oxygen consumption in bottom waters is a more important driver of oxygenation of bottom water than lake depth. By a positive feedback low bottom water oxygen concentrations can result in higher internal loading rates, which enhances algal productivity and the water quality deteriorates. However, definite evidence for enhanced internal loading requires comparisons of external loading, internal loading and nutrient burial rates.

Table 1. Number of lakes in each trophic level using the TLI in each region in 2005-2009.

RC	Microtrophic TLI 1-2	Oligotrophic TLI 2-3	Mesotrophic TLI 3-4	Eutrophic TLI 4-5	Supertrophic TLI 5-6	Hypertrophic TLI >6	Total
ARC			1	4	1	1	7
BOP		4	4	2	1		11
ECAN	6	12	9	1	2	4	34
ES		2		1			3
EW		1		3	3	3	10
GWRC					1		1
HBRC			3	1			4
HRC						1	1
NRC		3	11	11	2	2	29
ORC	2	2	1	2	3		10
TRC			1				1
WCRC		1					1
Total	8	25	30	25	13	11	112
Total %	7	22	27	22	12	10	

Table 2. Number of lakes in each trophic level using the TLI for each lake type in 2005-2009.

Lake type	Microtrophic TLI 1-2	Oligotrophic TLI 2-3	Mesotrophic TLI 3-4	Eutrophic TLI 4-5	Supertrophic TLI 5-6	Hypertrophic TLI >6	Total
Beach						1	1
Dune		3	12	12	3	3	33
Glacial	7	16	5	1	2		31
Lagoon				1	1	1	3
Landslide			1	1			2
Peat			3	3	3	1	10
Reservoir	1	1	2				4
Riverine				2	3	4	9
Volcanic		5	4	4	1		14
nd			3	1		1	5
Total	8	25	30	25	13	11	112
Total %	7	22	27	22	12	10	

nd = lake type is not determined.

Table 3. Number of lakes in each trophic level assessed using the TLI for each dominant land cover type.

Land cover	Microtrophic TLI 1-2	Oligotrophic TLI 2-3	Mesotrophic TLI 3-4	Eutrophic TLI 4-5	Supertrophic TLI 5-6	Hypertrophic TLI >6	Total
Alpine	2	1					3
Exotic		1	7	9	1		18
Native	5	16	12	5		1	39
Pastoral	1	7	10	10	12	10	50
Urban				1			1
nd			1				1
Total	8	25	30	25	13	11	112
Total %	7	22	27	22	12	10	

nd = land cover type is not determined.

Table 4. Median values for water quality variables in the four main land-cover classes (number of lakes in each class shown in brackets).

Variable	Alpine (3)	Native (39)	Exotic (18)	Pasture (50)
TN (mg/m^3)	40.0	149.0	477.0	773.4
TP (mg/m^3)	3.0	7.0	17.5	36.8
CHLA (mg/m^3)	0.5	1.6	4.7	8.8
SECCHI (m)	na	6.4	2.9	2.0
NH4-N (mg/m^3)	11.5	6.0	6.5	13.0
DRP (mg/m^3)	0.8	2.0	0.8	2.5
COND mS/cm	na	22.8	21.8	19.2
TURB (NTU)	1.1	0.8	na	3.2
pH	na	7.5	7.2	7.7
TLI3	1.6	2.8	4.1	4.7
TLI4	na	3.0	4.1	4.9

Notes: Total number of lakes for each variable ranged from 60 to 119 due to differences in monitoring programmes; na = no data available.

Table 5. Ecological condition assessed since 2005 using LakeSPI for each region.

RC	Excellent >75%	High 50-75%	Moderate 20-50%	Poor >0-20%	Non-vegetated 0%	Total
ARC	1	3	5	6	9	24
BOP		1	10	2		13
ECAN	3	8	8			19
ES		3				3
EW	3	3	10	8	25	49
HBRC	2		1	2	1	6
HRC						
NRC	13	10	11	2	1	37
ORC	1		1			2
WCRC			1	1		2
Total	23	28	47	21	36	155
Total %	15	18	30	14	23	

Table 6. Ecological condition assessed since 2005 using LakeSPI for each lake type.

Lake type	Excellent >75%	High 50-75%	Moderate 20-50%	Poor >0-20%	Non-vegetated 0%	Total lakes
Dune	10	7	11	3	2	33
Glacial	2	7	7			16
Landslide	1			2		3
Peat	1	2			6	9
Riverine		1		3	7	11
Volcanic	1	1	13	2	1	18
nd	8	10	16	11	20	65
Total	23	28	47	21	36	155
Total %	15	18	30	14	23	

nd = lake type is not determined.

Table 7. Ecological condition assessed since 2005 using LakeSPI for each land cover type.

Land cover	Excellent >75%	High 50-75%	Moderate 20-50%	Poor >0-20%	Non-vegetated 0%	Total lakes
Alpine	1					1
Exotic	6	6	10	1	2	25
Native	8	11	18	14	4	55
Pastoral	8	7	18	6	27	66
Urban		1			1	2
nd		3	1		2	6
Total	23	28	47	21	36	155
Total %	15	18	30	14	23	

nd = land cover is not determined.

Table 8. Distribution of 3820 lakes in New Zealand (>1 ha) in each of the water quality groups of Sorrell (2006).

Group	Environment description	Number of lakes	% of lakes	Median TLI
1	Very cold climates	1638	42.9	2.3
2	Cold winters but milder mean annual temperatures	674	17.6	3.2
3	Mild climates, >c. 50% native catchment cover	275	7.2	3.6
4	Mild climate, native and pasture cover are both < c. 50%, far northern	15	0.4	3.7
5	Mild climate, native and pasture cover are both < c. 50%	278	7.3	4.2
6	Mild climate, >50% pasture cover, lake area <0.60 km^2	906	23.7	5.0
7	Mild climate, >50% pasture cover, lake area >0.60 km^2	34	0.9	6.2
Total		3820	100	
Weighted mean				3.4

Table 9. The frequency of occurrence of low oxygen conditions in bottom waters in lakes. Lakes under stratified conditions (>3°C difference between surface and bottom) are compared with non-stratified lakes, and all lakes and measurements combined.

	2005-2009
All year	
Total number of lakes	63
Number of measurements	1822
Average bottom water DO (mg/L)	5.9
Number of lakes with average bottom DO < 3 mg/l	7
Percent lakes with average bottom DO < 3 mg/l	11
Stratified conditions	
Total number of lakes	46
Number of measurements	602
% of measurements that are stratified	33
Average bottom water DO (mg/L)	2.9
Number of lakes with average bottom DO < 3 mg/l	29
Percent lakes with average bottom DO < 3 mg/l	63
Non-stratified conditions	
Total number of lakes	63
Number of measurements	1220
Average bottom water DO (mg/L)	7.3
Number of lakes with average bottom DO < 3 mg/l	2
Percent lakes with average bottom DO < 3 mg/l	3.2

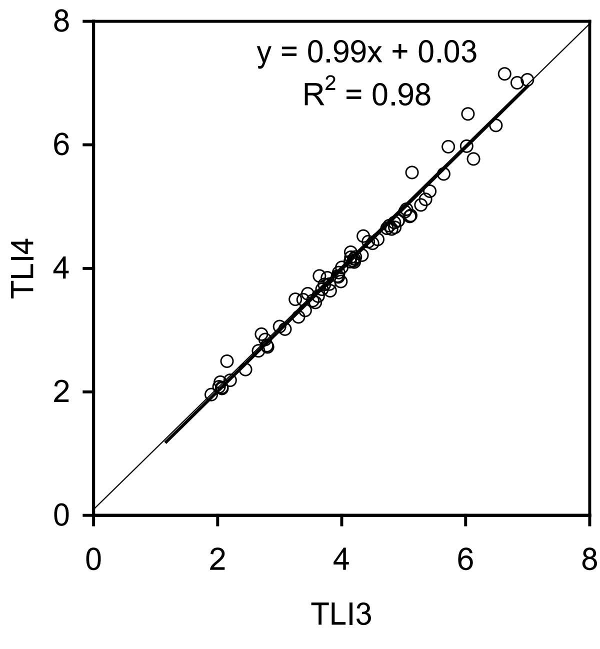

Figure 1: Comparison of TLI3 and TLI4. The 1:1 line is shown. The regression fit and TLI4=TLI3 line are almost indistinguishable.

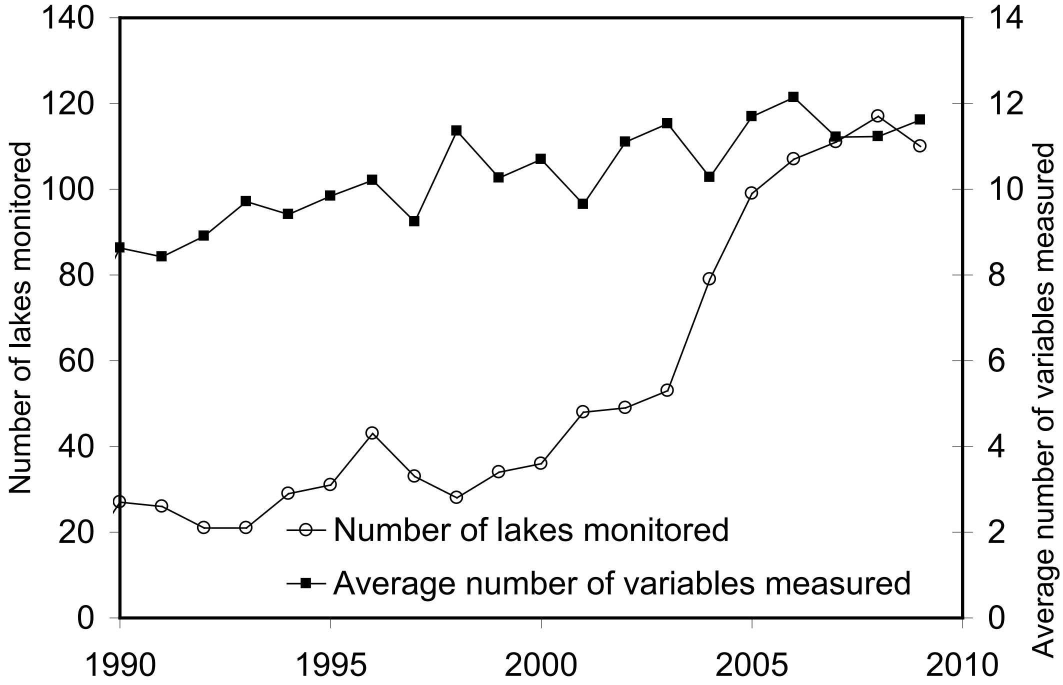

Figure 2: The number of lakes sampled as part of the long term monitoring program in each year since 1990 and the average number of variables that were measured in each lake.

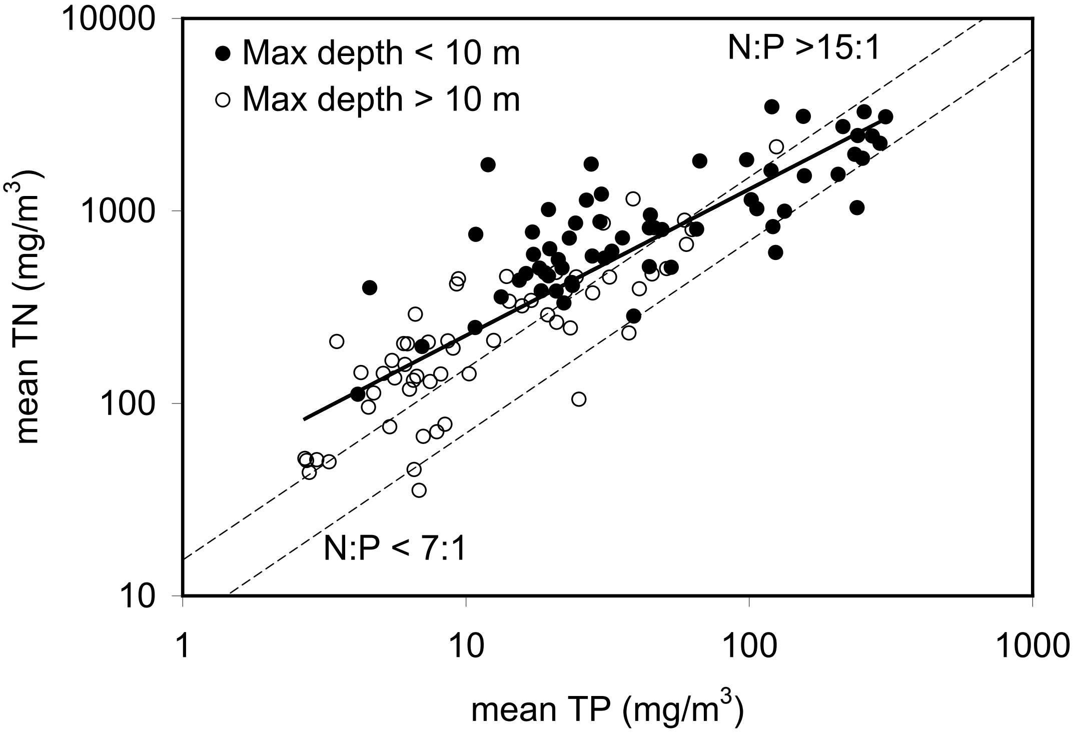

Figure 3: Relationship between total phosphorus (TP) and total nitrogen (TN) for shallow lakes (<10 m maximum depth) and deep lakes (>10 m maximum depth). The regression is for all lakes (R^2 = 0.74). Dashed lines demarcate N:P ratios of 7:1 and 15:1. Ratios lower than 7:1 and higher than 15:1 are sometimes considered to suggest potential N-limited and P-limited algal growth (Sorrell 2006), respectively, but see discussion in text.

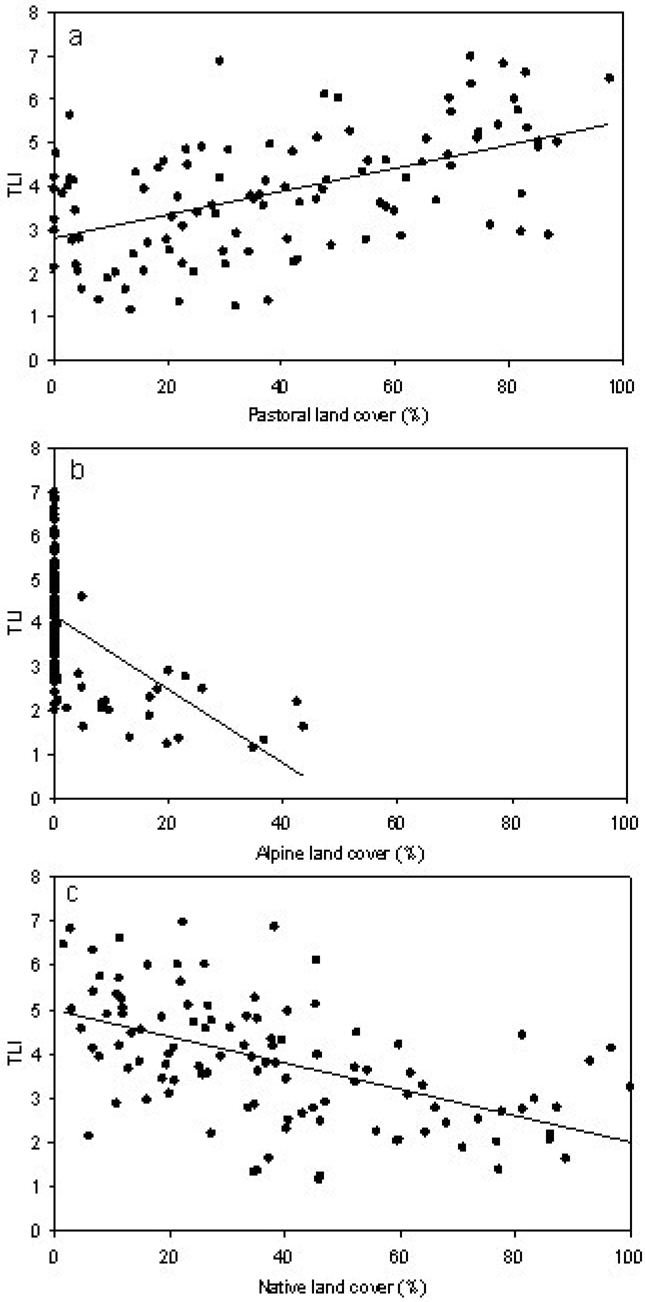

Figure 4: Relation between TLI3 and percentage (a) pastoral (R^2 = 0.27), (b) alpine (R^2 = 0.30), and (c) native land cover (R^2 = 0.28) in the catchment.

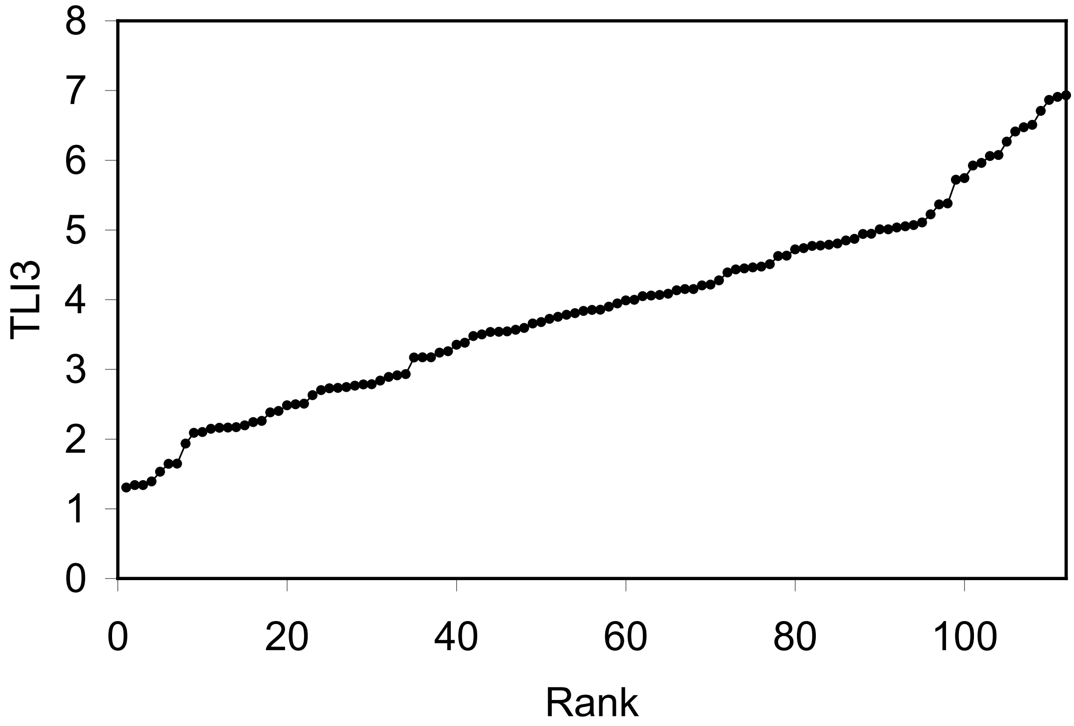

Figure 5: Rank distribution of TLI3 among the 112 lakes monitored in 2005-2009.

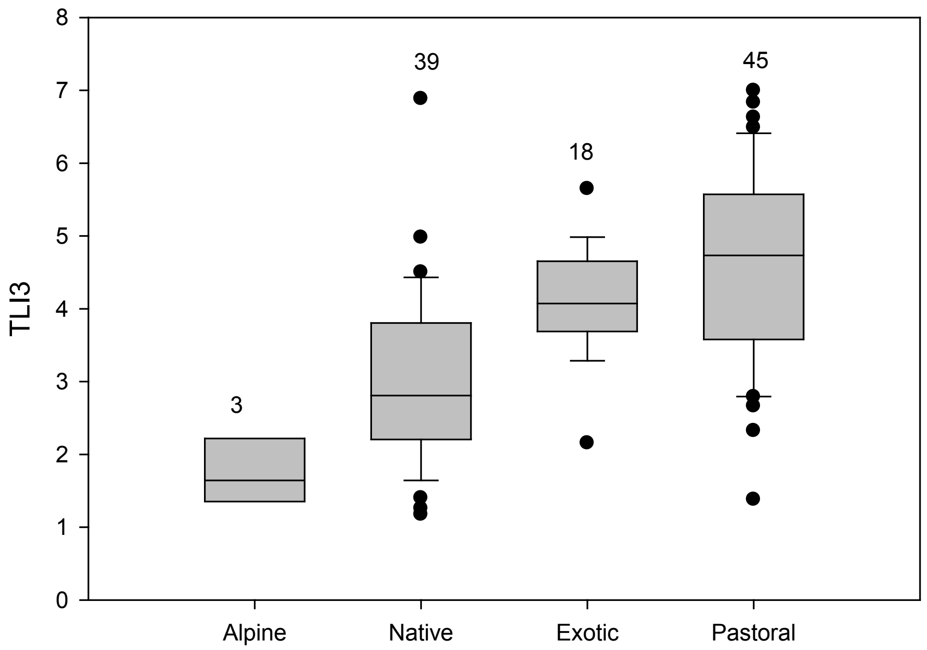

Figure 6: Box and whisker plots showing differences in TLI in four classes of predominant land cover. Numbers indicate sample size. Horizontal lines within boxes show median values, boxes show 25–75% data ranges, whiskers show 5–95% ranges, and circles outliers outside the 5–95% ranges.

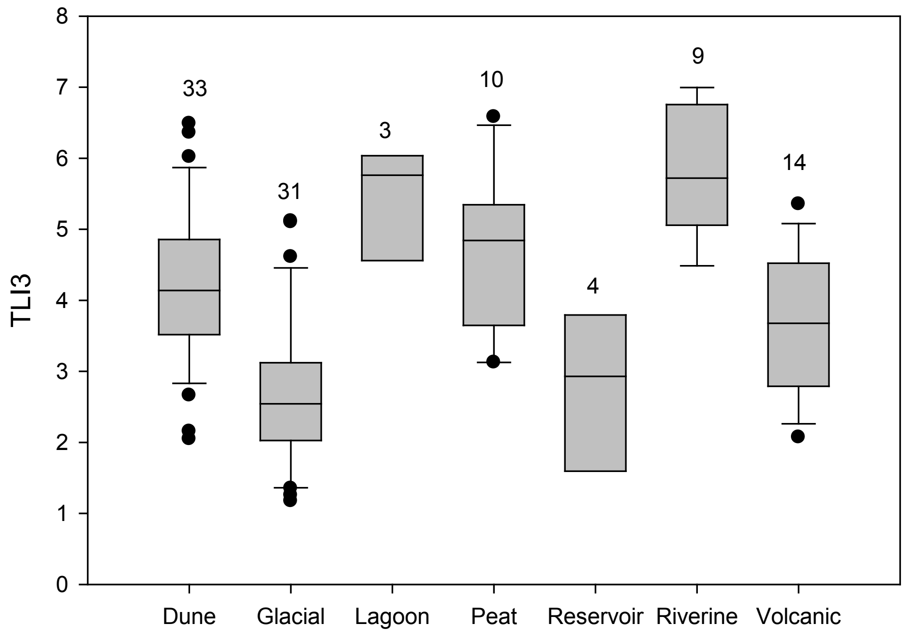

Figure 7: Box and whisker plots showing differences in TLI in seven classes of lake type. Numbers indicate sample size. Horizontal lines within boxes show median values, boxes show 25–75% data ranges, whiskers show 5–95% ranges, and circles outliers outside the 5–95% ranges.

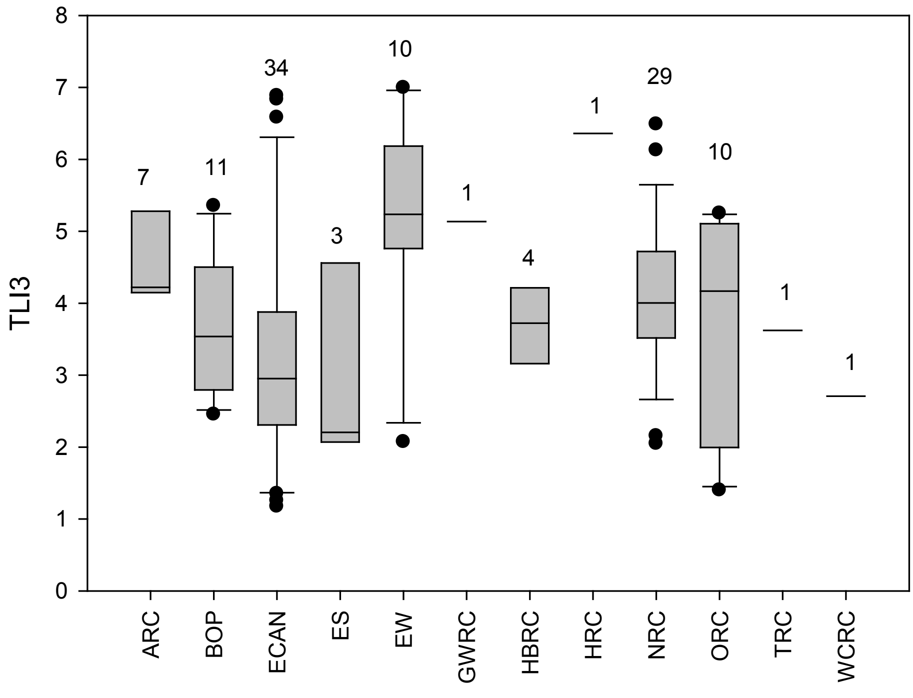

Figure 8: Box and whisker plots showing differences in TLI between 12 regions. Numbers indicate sample size. Horizontal lines within boxes show median values, boxes show 25–75% data ranges, whiskers show 5–95% ranges, and circles outliers outside the 5–95% ranges.

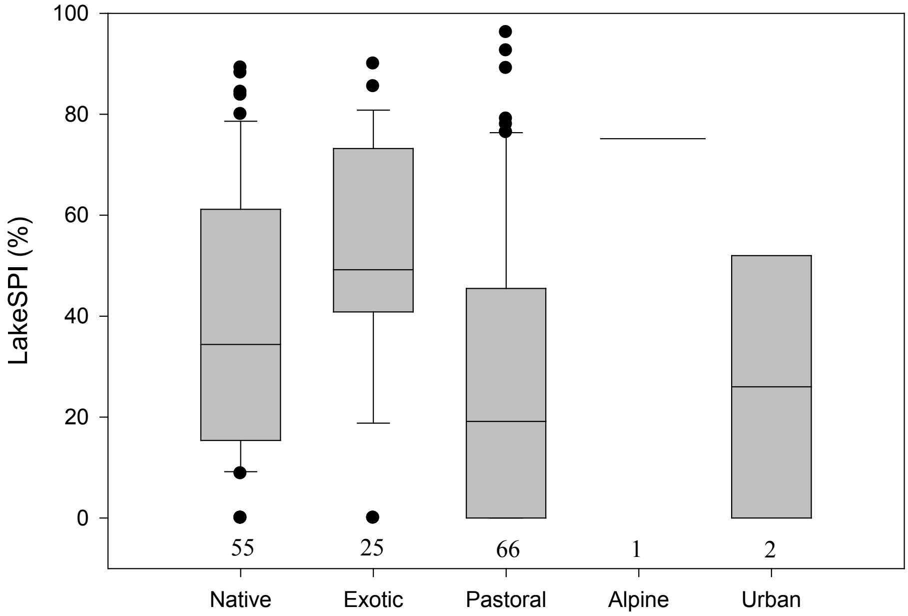

Figure 9: Box and whisker plots showing differences in LakeSPI in five classes of predominant land cover. Numbers indicate sample size. Horizontal lines within boxes show median values, boxes show 25–75% data ranges, whiskers show 5–95% ranges, and circles outliers outside the 5–95% ranges.

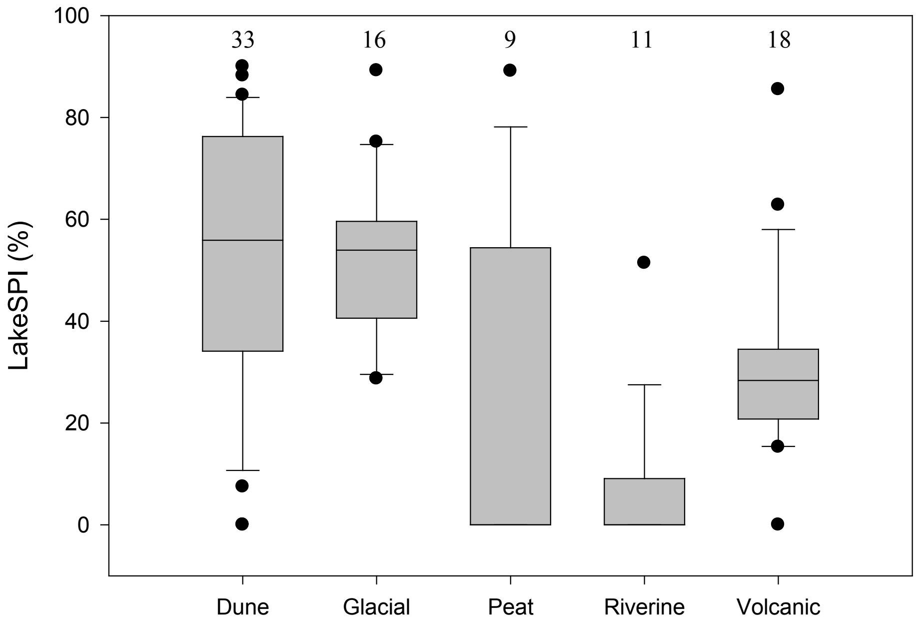

Figure 10: Box and whisker plots showing differences in LakeSPI in five classes of lake type. Numbers indicate sample size. Horizontal lines within boxes show median values, boxes show 25–75% data ranges, whiskers show 5–95% ranges, and circles outliers outside the 5–95% ranges.

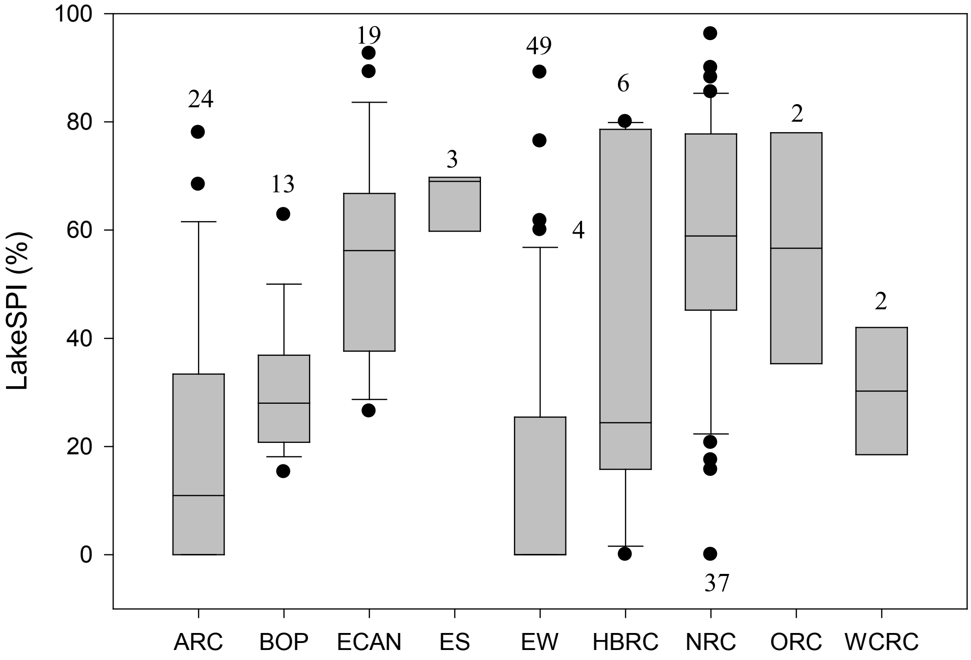

Figure 11: Box and whisker plots showing differences in LakeSPI between 10 regions. Numbers indicate sample size. Horizontal lines within boxes show median values, boxes show 25–75% data ranges, whiskers show 5–95% ranges, and circles outliers outside the 5–95% ranges.

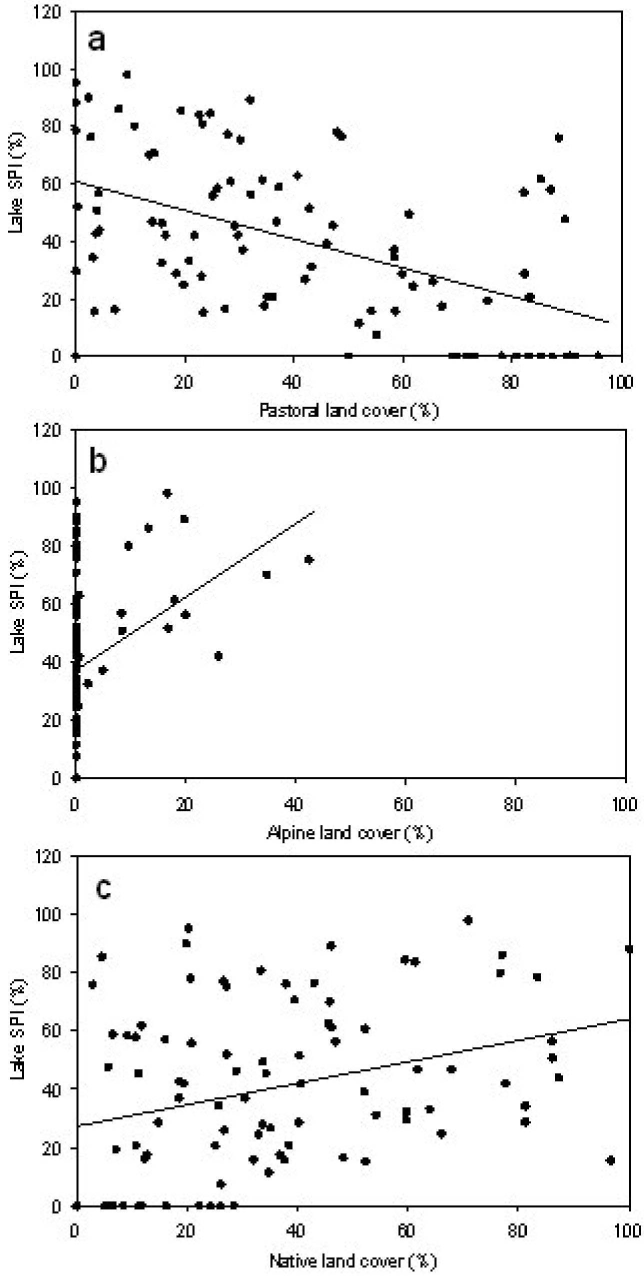

Figure 12: Relation between lakeSPI and percentage (a) pastoral (R^2 = 0.26), (b) alpine (R^2 = 0.11), and (c) native land cover (R^2 = 0.10) in the catchment.

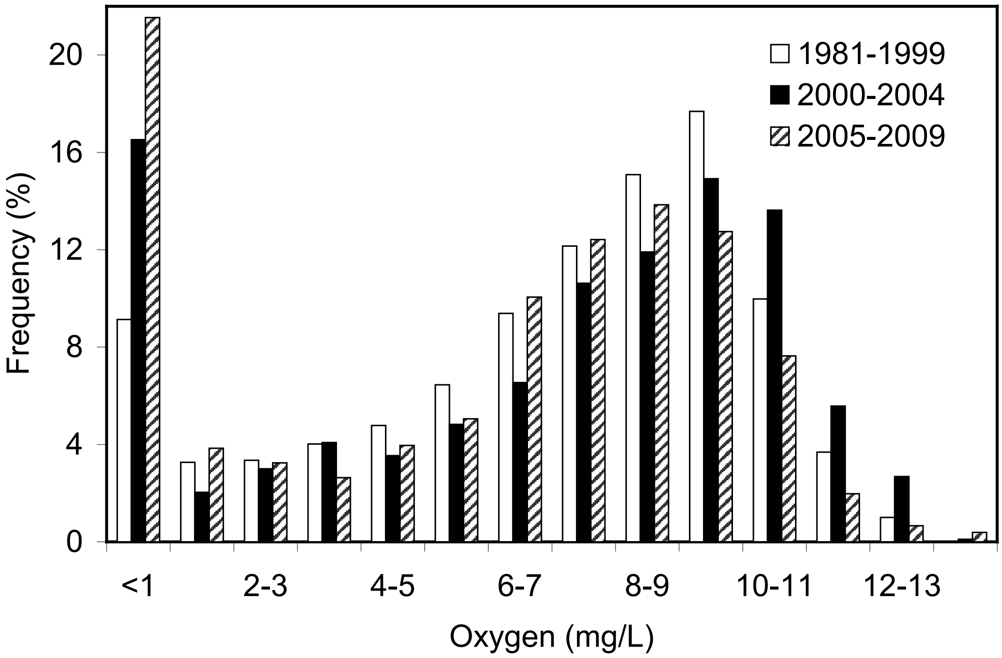

Figure 13: Frequency distributions of oxygen concentrations in bottom waters comparing 1981-1999 (n = 1193 measurements in 13 lakes), 2000-2004 (n = 932 measurements in 21 lakes) and 2005-2009 (n = 1822 measurements in 63 lakes).

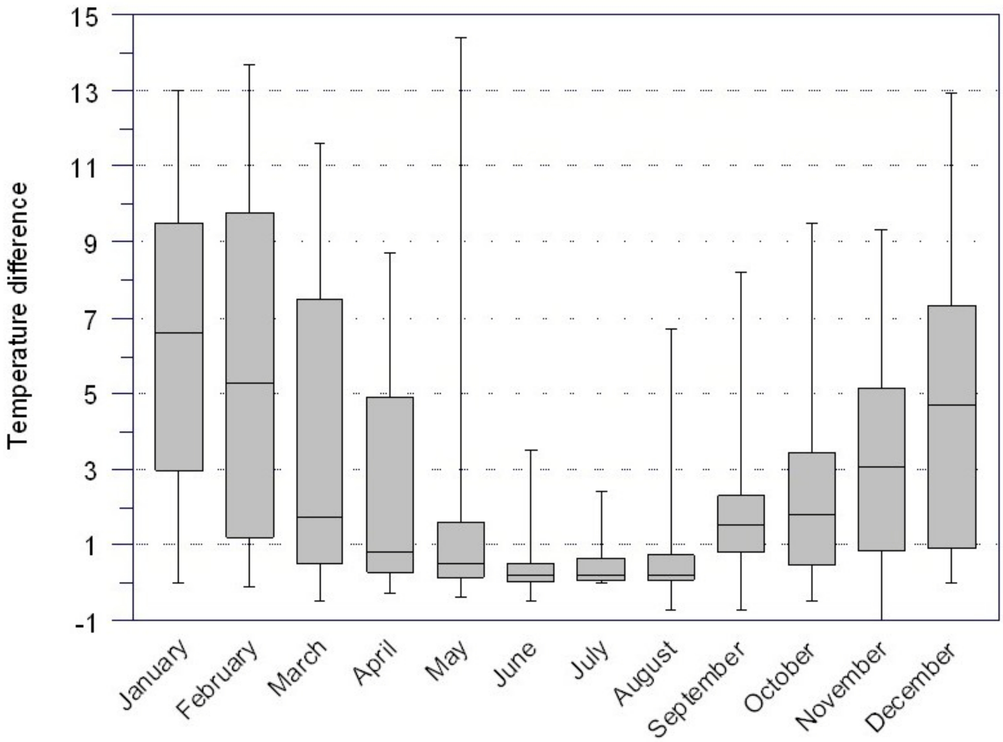

Figure 14: Seasonal distribution of temperature differences (°C) between surface and bottom waters in 63 lakes in 2005-2009.

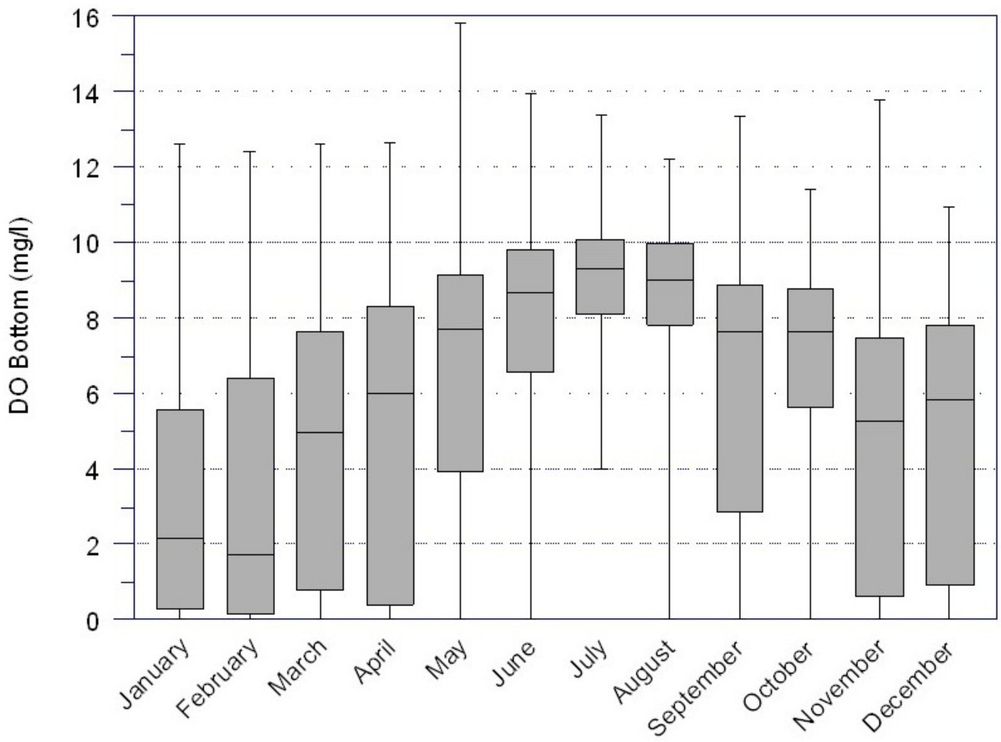

Figure 15: Seasonal distribution of dissolved oxygen in bottom waters in 63 lakes in 2005-2009.

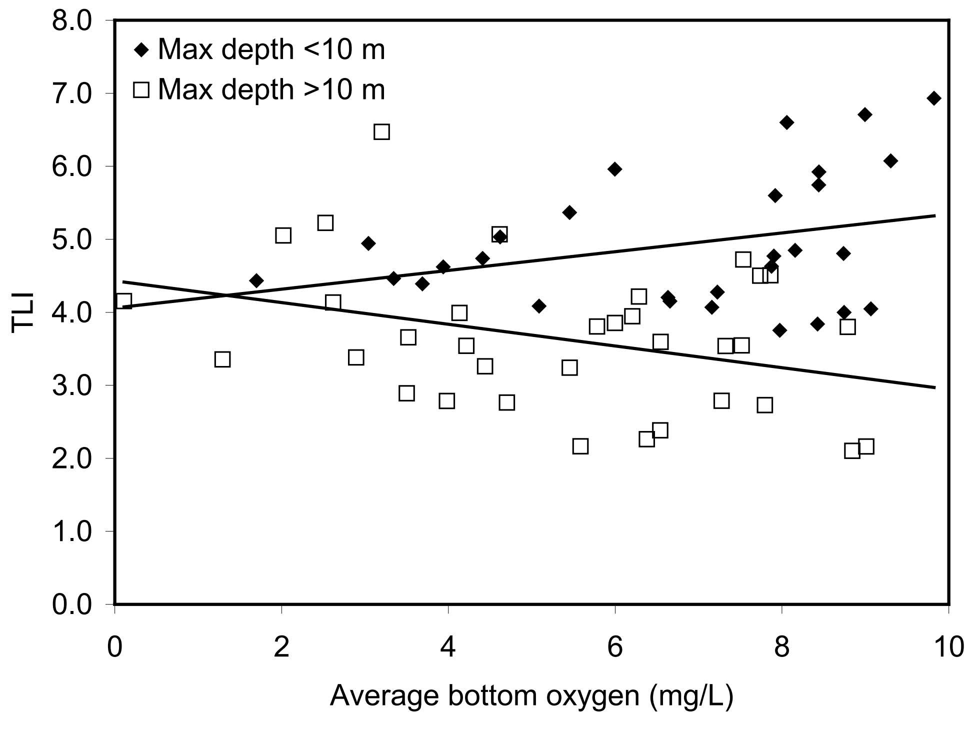

Figure 16: The relation between TLI and average bottom water oxygen concentrations in lakes of different depths, suggesting that in lakes >10 m deep low oxygen concentrations in bottom water are more prevalent in the more productive lakes.

3. Lake water quality trends

3.1 Methods

Time trend analysis was undertaken using quarterly means for the periods 2005-2009 (5 years), 2000-2009 (10 years), and 1990-2009 (20 years, subject to availability of data)[4]. When assessing the significance of these trends we limited our analysis to data sets with about 80% of quarterly data available (i.e., at least 16, 32 and 60 records respectively for the 5, 10, and 20 year quarterly trends[5]), as was done in the river water quality analysis for MfE (Ballantine et al., 2010). In addition, lakes with a seasonally stratified sampling regime (i.e., summer time only) were included when at least four monthly samples were collected in the same months each year. Only in the Canterbury high country lakes was sampling restricted to summer. The seasonal Mann-Kendall trend test was used[6] and trends were recorded as significant (in Tables 10 to 13) when $p < 0.05$. The sign of the Kendall tau value indicates the direction of the change.

The seasonal Mann-Kendall test does not account for serial correlation within each time series, which – if present – could falsely identify non-significant trends as significant. In practice, serial correlation is unlikely to have occurred because most data were recorded (and analysed) quarterly rather than monthly, thereby weakening any serial correlation. Moreover, statistical tests for serial correlation do not work well for data sets shorter than ten years (Hirsch and Slack 1984).

While changes in water quality variables are considered significant when $p < 0.05$, the changes are deemed *meaningful* when higher than 1% per year relative to the median, following Scarsbrook (2006).

3.2 Results and discussion

Trends in various water quality variables were analysed for 18 lakes for the period 2000-2009 (see Table 10). Three of these lakes (17%) had deteriorated significantly (increased 2.0 to 2.8% per year in TLI) since 2000 (two in the BOP region and one in Otago), and one lake (6%) had improved significantly (Lake Omapere in Northland, by 2.0% per year in terms of TLI). Of three lakes for which sufficient data were available for the period 1990-2009 (Table 10), one lake increased significantly in TLI

4 Monthly data was also analysed, but for far fewer lakes and has not been reported.
5 60 out of 80 quarters since 1990, 32 out of 40 quarters since 2000 and 16 out of 20 quarters since 2005.
6 Using the package Kendall for the R Statistical Language and Environment for Statistical Computing (McLeod 2009, R Development Core Team 2009).

(Lake Rerewhakaaitu, 0.5% per year; not a meaningful trend following guidelines in Scarsbrook, 2006).

Appendix 1 presents the percent annual change (PAC) in TLI for all lakes during 2005-2009 for which sufficient data were available, together with significance levels. All significant PAC's for the past 5 years are >2% and are therefore meaningful.

Trends for various water quality variables were analysed for 68 lakes for the period 2005-2009 (Table 10). This found 19 lakes (28%) had deteriorated significantly (increased in TLI by 2.2% to 21.4% per year, average 8.6%) since 2005 (two in BOP region, one in Southland, one in Northland and 15 in Canterbury). Lake Coleridge increased most in TLI (21.4% per year, from an average 1.0 in 2005 to an average 2.1 in 2009) which was mostly driven by an increase in chlorophyll a, but Lake Coleridge is still the lake with the lowest TLI of all monitored lakes (average 1.3 for 2005-2009, appendix 1). The water quality in Waituna Lagoon (Southland) may have been adversely affected by the opening and closing of the lagoon. The eight lakes (12%) that had improved significantly were spread over several regions (ECAN: lake Forsyth, 3.2% decrease per year in TLI; ES: Lakes Manapouri and Te Anau decreased 4.1 and 8.9% per year in TLI, respectively; EW: Lake Hakanoa decreased 3.6% per year in TLI; and NRC: four lakes decreased 4.1 to 12.7% per year in TLI). The average decrease in TLI for the eight improving lakes was 6.2% per year, less than the average increase in the deteriorating lakes (8.6%).

The mean TLI in all lakes in 2005-2009 was slightly lower compared with 2004-2006, from 4.1 in 2004-2006 to 3.9 in 2005-2009, without considering significance of trends in individual lakes (see columns 10-12 in appendix 1). A comparison of the lakes assessed both in Sorrell (2006) and in this report (n = 93) found that there was a decrease in mean TLI, from 4.0 in 2004-2006 to 3.8 in 2005-2009. The decrease in mean TLI was significant (paired t-test, df = 92, t = 3.03, $p < 0.005$). Median TLI decreased slightly in each of the four dominant land cover classes (compare Table 4 with Table 5 in Sorrell 2006). Although the trends in the period 2005-2009 (above) and the comparison of the mean of 2005-2009 with the means in Sorrell (2006) compares different periods, the result is likely explained in part by the fact that the improving lakes were on average higher in TLI than the deteriorating lakes. The lakes that improved significantly in TLI during 2005-2009 (i.e., TLI declining; appendix 1) had an average TLI of 4.1 while the average TLI of deteriorating lakes (i.e., TLI increasing) was 3.0. In particular the lakes in Canterbury that declined are low in TLI. In other words, more lakes declined than improved and overall lake condition improved slightly.

The results of trend analysis are shown in Tables 10 to 13. Seven of the lakes monitored since 1990 (and for which sufficient data were available for a trend analysis, n = 13) increased significantly in TP (Table 10; by 1.4 to 5.0% per year), while one decreased in TP (Lake Wainamu, 2.3% per year). Secchi disk transparency increased significantly in more lakes than in which it decreased (Table 10), in 1990-2009 (4 lakes, by 0.9 to 5.0% per year), 2000-2009 (8 lakes, by 3.9 to 13.8% per year) and in 2005-2009 (5 lakes, by 9.0 to 14.2% per year). It must be noted that the lakes for which sufficient data were available for trend analysis of Secchi disk transparency are not necessarily the same lakes as those for TN, TP and chlorophyll concentrations.

Comparison of trends between regions, lake types and land cover (Tables 11-13) was done using the period 2005-2009, because very few lakes had sufficient quarterly data in the period 1990-2005[7]. Additionally, in Sorrell (2006) and Hamill (2006) the period used for trend analysis was also 5 years or less for many lakes.

At the national scale there were twice as many deteriorating lakes as improving lakes. Sixty percent of lakes showed no change since 2005 (Table 11). Canterbury region had the greatest number of deteriorating lakes (increasing TLI) since 2005, with more than half of lakes assessed showing a decline (by 5.6 to 20.7% increase per year in TLI). Lake Forsyth in Canterbury improved (3.2% decrease per year in TLI). In contrast Northland region had a third of its lakes showing a significant improvement (4.1 to 12.7% per year decrease in TLI). All the declining lakes in Canterbury were glacial lakes, with either dominant native (8 out of 15) or pastoral cover (7 out of 15). Thus glacial lakes showed a decline, while about half of the improving lakes were dune lakes (Table 12).

Almost 40% of lakes with dominant native catchment cover and a quarter of lakes with dominant pastoral cover (Table 13) declined significantly in water quality. Nine lakes with dominant native cover increased 2.2 to 20.7% per year in TLI with an average 10.1% per year increase (eight of these lakes were in Canterbury). Nine lakes with dominant pastoral cover increased 3.9 to 12.0% per year in TLI with an average 7.2% per year increase. Declines in pastoral lakes are to be expected with nutrient mobilisation from livestock, but the change in lakes with (predominantly) native cover is, at first, surprising. However, even small proportions of catchments in pasture (where native cover predominates) can yield appreciable nutrients, which could be driving the recorded TLI increase since 2005. It is possible that the nutrient loading increased from the pastoral sections in catchments where native cover is dominant.

Changes in temperature were not significant for any of the lakes, for any of the periods examined (1990-2009, 2000-2009 and 2005-2009), unlike temperatures in rivers which increased significantly at 13 sites, out of a total of 77 sites during 1988-2007 (Ballantine & Davies-Colley 2009). However, the period examined for trends in most

[7] See Table 10 which distinguishes between trends since 1990, 2000 and 2005, and gives the number of lakes in the sample (for instance only 18 lakes for TLI since 2000).

lakes was shorter than the 20 years in the river water quality study (which could rely on more consistent sampling, with monthly samples throughout the period), and in the twenty years of 1990-2009 sufficient data was available for only three lakes.

Where LakeSPI was recorded multiples times in lakes it suggested that ecological condition declined in 28% of lakes and improved in 11% of lakes (n = 110 lakes; Table 14). However, the periods over which LakeSPI trends have been calculated differed for each lake and were based on different numbers of sampling occasions. Therefore these trends must be considered with caution and are not as robust as the trends determined for TLI.

Figure 3 shows that the TN:TP ratio is >15 in the majority (85%) of NZ monitored lakes. In lakes where the TN:TP ratio is >15, algal growth is sometimes considered to be potentially phosphorus limited, and in lakes where the ratio is <7, potentially nitrogen limited (Sorrell 2006). However, nutrient ratios cannot be unequivocally interpreted in terms of nutrient limitation because of differences in nutrient requirements depending on the algal composition and because a component of the nutrients may be locked up in relatively unavailable forms (Pridmore 1987). The number of lakes where the TN:TP mass ratio is <7 has decreased to five lakes (averages of 2005-2009) compared to 18 lakes in the analysis of Sorrell (2006) for 2004-2006 (Fig. 3; compare with Fig. 2 in Sorrell [2006]). The lakes where TN:TP was <7 in 2005-2009 were Basin Reserve, Pukaki, Rotomahana, Ototoa and Wairarapa. Compared to the lake data set of Sorrell (2006), the median TN concentration in lakes with dominant pasture cover increased 5.5%, while the median TP concentration in lakes with dominant pasture cover decreased 28% (Table 4, compare with Table 5 in Sorrell [2006]). The median TN concentration in lakes with other dominant cover types was not higher than in Sorrell (2006). The difference from the result in Sorrell (2006) may be in part related to the fact that the present lake data set does not contain exactly the same lakes as in the analysis by Sorrell (2006; 93 lakes out of a total of 112 lakes in the current analysis were also present in the lake water quality report of 2006; appendix 1). However, the change in the TN:TP ratio appears to be real. Since 2005, more lakes increased in TN concentration than lakes that increased in TP (Table 10). A shift towards potential P-limitation of NZ lakes would be consistent with more rapid nitrogen enrichment than phosphorus enrichment over most of New Zealand as suggested by trends in river water quality (Ballantine & Davies-Colley 2009). However, caution is required when interpreting nutrient ratios in terms of limitation for algal growth (see above).

Table 10. Trends in water quality variables. Number of lakes for which at least 80% of quarterly data are available, and number of lakes where the variable significantly increased (+) or decreased (-), while trends in the remainder were not significant.

Variable	1990-2009	2000-2009	2005-2009
TLI3	3 (1+, 0-)	18 (3+, 1-)	68 (19+, 8-)
TLI4	3 (0+, 0-)	13 (2+, 1-)	22 (2+, 3-)
TN	4 (1+, 0-)	20 (2+, 4-)	70 (16+, 10-)
TP	13 (7+, 1-)	30 (8+, 5-)	75 (11+, 11-)
CHLA	11 (1+, 2-)	28 (2+, 3-)	77 (19+, 3-)
SECCHI	16 (4+, 2-)	21 (8+, 1-)	33 (5+, 2-)
DRP	15 (1+, 0-)	29 (7+, 4-)	52 (0+, 8-)
NH4N	15 (2+, 3-)	28 (6+, 5-)	53 (7+, 3-)
NNN	15 (3+, 3-)	27 (4+, 3-)	49 (3+, 2-)
COND	2 (2+, 0-)	4 (1+, 0-)	23 (6+, 3-)
pH	13 (5+, 0-)	27 (2+, 2-)	48 (0+, 5-)
SS	7 (2+, 2-)	15 (3+, 2-)	36 (4+, 5-)
TURB	11 (4+, 0-)	27 (3+, 2-)	57 (6+, 5-)

Table 11. Changes in trophic state (TLI) for each region since 2005.

Regional council	Declining quality	No change	Improving quality	Total
BOP	2	9		11
ECAN	15	10	1	26
ES	1		2	3
EW		8	1	9
NRC	1	8	4	13
ORC		5		5
WCRC		1		1
Total	19	41	8	68
Total %	28	60	12	

Table 12. Changes in trophic state (TLI) for each lake type since 2005.

Lake type	Declining quality	No change	Improving quality	Total
Dune	1	8	3	12
Glacial	15	6	2	23
Lagoon	1	3	1	5
Riverine		5	1	6
Volcanic	2	10	1	13
Peat		8		8
Reservoir		1		1
Total	19	41	8	68
Total %	28	60	12	

Table 13. Changes in trophic state (TLI) for each land cover since 2005.

Land cover	Declining quality	No change	Improving quality	Total
Alpine		2		2
Exotic	1	4	1	6
Native	9	12	3	24
Pastoral	9	22	4	35
Total	19	40	8	67
Total %	28	59	12	

Table 14. Trends in LakeSPI.

Region	Declining	Stable	Improving	Total
Auckland	7	7	6	20
Canterbury	3	6		9
Bay of Plenty	6	5	1	12
Waikato	7	33	3	43
Hawkes Bay		1		1
Northland	8	14	2	24
West Coast		1		1
Grand Total	31	67	12	110
Total %	28	61	11	

4. International comparison of lake water quality

The purpose of this section is to place New Zealand lake water quality in an international context by providing a comparison of data relating to water quality between lakes in New Zealand, the USA, Canada and Europe.

4.1 Methods

The status of NZ lake water quality as reported above was compared with data available from lakes elsewhere to provide an international comparison. In-lake concentrations of total phosphorus, total nitrogen and chlorophyll *a* were obtained from the following sources:

- Europe (n = 716): European Environment Agency (2009) Waterbase-Lakes Quality database.

- USA (n = 483): 1) Central Plains Center for BioAssessment; and 2) Jones et al., (2008).

- Canada (n = 50): Murphy et al., (2010).

- New Zealand (n=113): New Zealand Ministry for the Environment and New Zealand Regional Councils. Data are mean values for 2005 – 2009.

It is important to note that the data are not necessarily representative of the range and average productivity status of lakes in each respective geographic region. Effort has been made to source data for a large sample of lakes from each region however, when making broad generalisations, we acknowledge that regions such as the USA contain a large range of different lake types along a continuum of human disturbance that spans several climatic zones. The data for New Zealand lakes are likely to be the most nationally representative as they relate to a relatively large sample size (in proportion to overall geographic area) and they include data for a range of lake types from throughout the country. The USA data relate to lakes in seven Midwestern states and the Canadian data typically relate to remote or alpine lakes that are subject to a level of human disturbance that is not representative of lakes in more populous regions of Canada. The European lake data are a compilation of state of the environment data for 17 countries. Lakes from Sweden (n = 149), Italy (n = 152) and Finland (n = 245) are disproportionally represented in the European dataset.

The Trophic Level Index (TLI) is an aggregate measure of lake productivity indicators, developed using data for 23 New Zealand lakes (Burns et al., 1999). A key difference between the TLI and, for example, the Trophic State Index that is used widely in the USA (Carlson 1977) and the fixed boundary system developed by the OECD (1982) is that the latter two do not include a measure of TN while TLI does. A comparison of lake productivity measures between New Zealand lakes and lakes elsewhere in the world would be useful to understand and appreciate the water quality in our lakes relative to a very large sample of lakes around the world. We have used chlorophyll a concentrations to compare the productivity of lakes in NZ and international lakes, rather than the TLI because the TLI scheme was developed specifically for New Zealand lakes and has not been validated for international lakes in terms of its appropriateness as an index of trophic state (Burns et al., 1999).

4.2 Results and discussion

Comparison of lake productivity variables

There is considerable variation in the range and median of lake productivity variables between the four geographical categories (see Table 15). Overall, the median and the range of TN and TP concentrations are lowest for the Canadian lakes and highest for the USA lakes (Figs. 17; 18a, b). This reflects the relatively low and high levels, respectively, of human disturbance in the catchments of these two groups of lakes. The lowest TN concentrations are found in Canadian lakes (Fig. 17) and median TN is lower in the New Zealand lakes compared to the lakes in the USA and Europe (Fig. 18a). Nitrogen concentrations have previously been shown to be low in unproductive New Zealand lakes compared to unproductive lakes in other developed regions; a finding that has been attributed to relatively low rates of atmospheric nitrogen deposition in New Zealand (White, 1983). Unlike TN, median TP is comparable between the European lakes (21.2 mg m^{-3}) and the New Zealand lakes (20.8 mg m^{-3}). Although the median TP concentrations for the two groups of lakes are similar, a previous study has shown that median TP concentrations in medium (mesotrophic) and highly productive (hypertrophic) lakes in New Zealand are significantly higher than in European lakes of equivalent trophic state (Abell et al., 2010). This finding was attributed to high phosphorus inputs associated with pastoral agriculture (e.g., fertiliser application) in New Zealand. In addition, natural sources of phosphorus associated with some volcanic soils in New Zealand have been shown to be unusually high, contributing to elevated phosphorus concentrations in water bodies at regional (Timperley, 1983) and local scales (Quinn & Stroud, 2002). Statistics for chlorophyll *a* concentration (Fig. 18c) reflect the trends in nutrient data. Overall, the median and the range of chlorophyll *a* concentrations are lowest for the Canadian lakes and highest for the USA lakes. Median chlorophyll *a* concentration for the European lakes (5.4 mg m^{-3}) is slightly higher than for the New Zealand lakes (4.2 mg m^{-3}).

Table 15. Summary statistics of lake productivity parameters for lakes in Europe, the USA, Canada and New Zealand.

Region	n	Chlorophyll *a* (mg m-3)		Total nitrogen (mg m-3)		Total phosphorus (mg m-3)	
		Range	Median	Range	Median	Range	Median
Europe	716	0.1 – 218.6	5.4	124.2 – 7683.3	630.4	2.0 - 711.5	21.2
USA	483	1.1 – 467.1	15.5	70 - 17600	910	6.0 – 2420.0	61.2
Canada (alpine lakes)	50	0.1 – 19.4	1.4	58 - 1182	371	2.0 - 65	9
New Zealand	113	0.4 - 218.9	4.2	35.3 – 3275.2	444.2	2.7 – 289.5	20.8

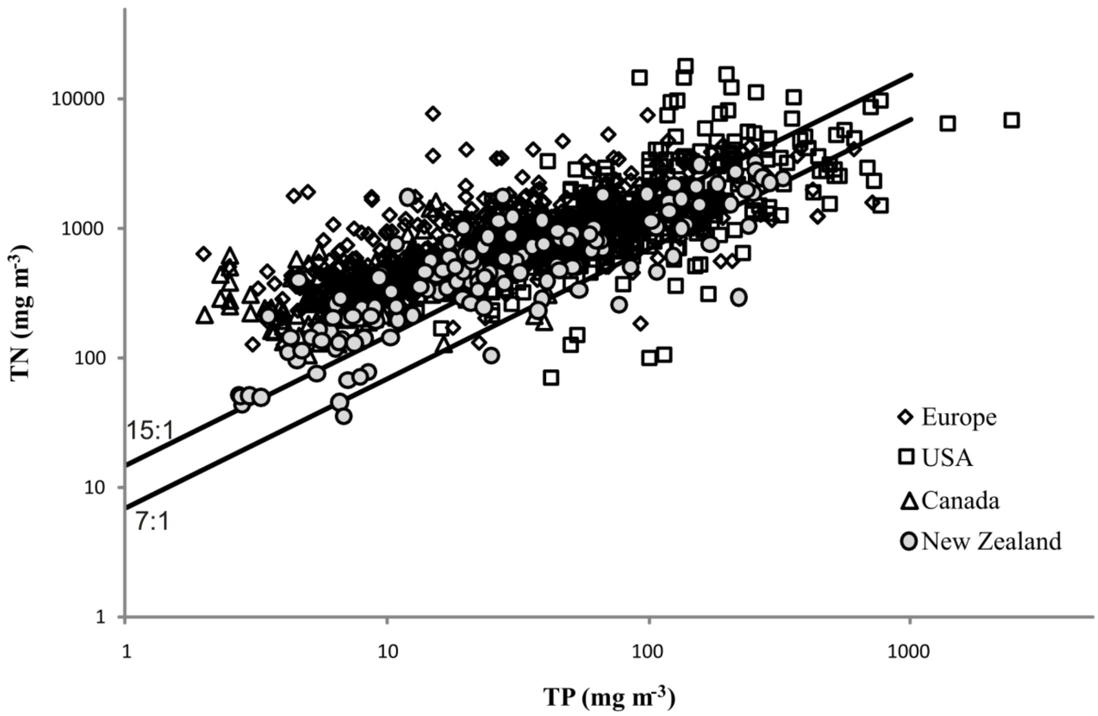

Figure 17: Total nitrogen (TN) and total phosphorus (TP) concentrations for 1473 lakes in Europe, USA, Canada and New Zealand. Data are on $\log_{10}$ scales. The solid lines show mass ratios of TN to TP of 7:1 and 15:1.

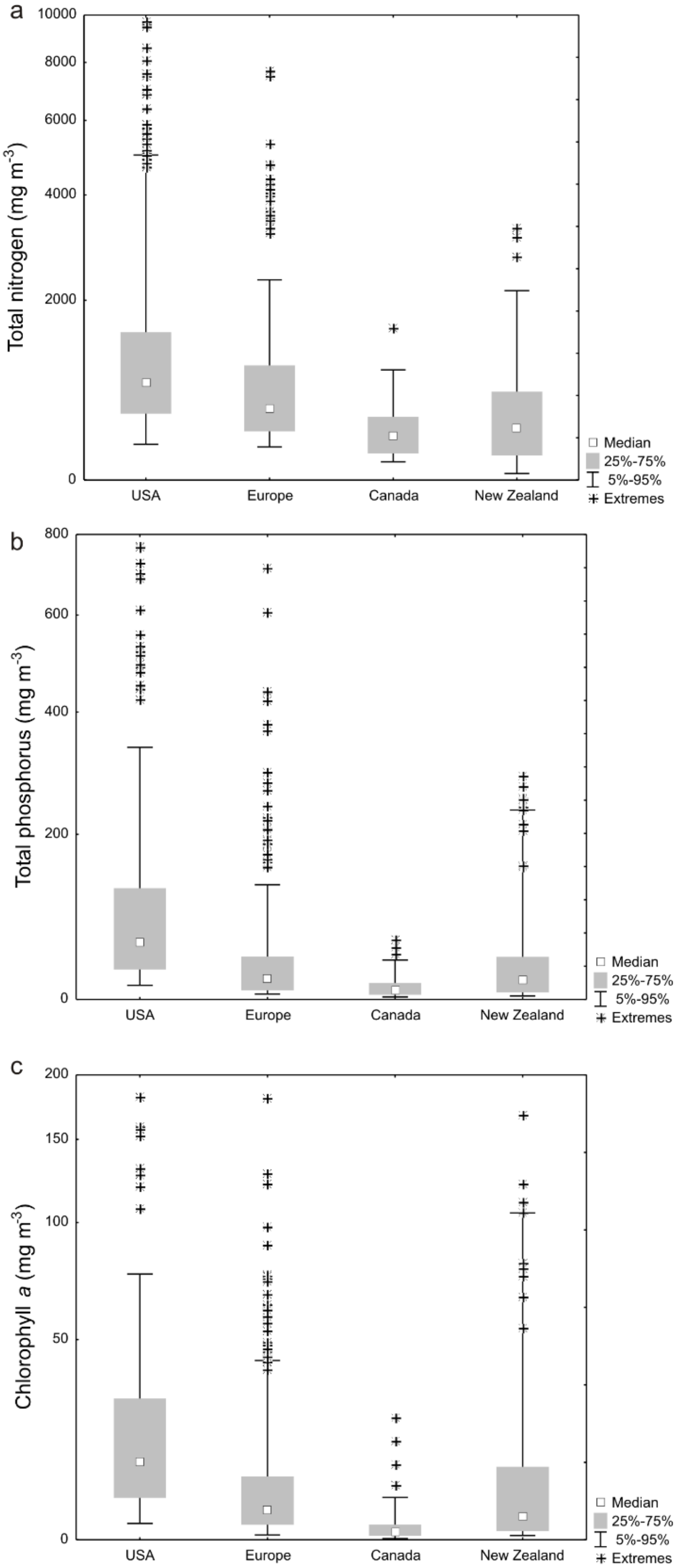

Figure 18: Total nitrogen (a), total phosphorus (b) and chlorophyll a (c) concentrations for 1473 lakes in the USA, Europe, Canada and New Zealand. Note that scales have been adjusted on box plots and therefore some extreme data points are not shown.

5. Summary and conclusions

New Zealand lakes are on average 'mesotrophic'. The highest water quality (i.e., oligotrophic) is typical of cold alpine and southern lakes in catchments with mostly native land cover (43% of lakes), and the poorest water quality (i.e., eutrophic to hypertrophic) typical of warm lakes with catchments having high pasture land cover (32% of lakes), confirming results in the 2006 analysis (Sorrell 2006).

Dissolved oxygen and temperature show that 63% of monitored lakes have hypoxic conditions in the bottom waters when stratified. Low dissolved oxygen (DO) concentrations in the bottom water of lakes is a concern because of the risk of the release of nutrients from lake sediments and consequent acceleration of eutrophication.

Monitoring of ecological condition using LakeSPI suggests that New Zealand lakes are on average in 'moderate' condition. There is a wide variation in ecological condition according to lake type and landuse.

Recent water quality trends (since 2005) show that 19 lakes (28%) have deteriorated (increased in TLI) since 2005 and eight lakes (12%) have improved. There is evidence of significant declines in water quality in many lakes that have more native than pastoral or other types of land cover and in many glacial lakes (with some catchment development) since 2005. Although more lakes declined than improved, the mean water quality across all monitored lakes (as indicated by TLI) did not decline since the previous survey (Sorrell 2006), and may have improved slightly (see comparisons for individual lakes in appendix 1). There was a slight (but significant) decrease in mean TLI (indicating improved condition) because the lakes that declined were on average oligotrophic while the improving lakes were on average eutrophic.

The declining trend in water quality in 15 of the glacial lakes in Canterbury seems consistent with increases in nutrients in Canterbury rivers (Ballantine 2009). The change in water quality in the oligotrophic glacial lakes in Canterbury (average TLI = 2.7 in the 15 deteriorating lakes) may be a result of the fact that monitoring started in these lakes in December 2004, during a period of drought, when inflows and nutrient loading rates to these lakes were low (Sorrell 2006). The more recent nutrient concentrations possibly reflect more normal conditions in these lakes. On the other hand, nutrient enrichment may be derived from pastoral areas in these lake catchments. In addition, an increase in trophic level of naturally oligotrophic waters may be explained as an effect of increasing temperatures which have been recorded in NZ waters (Ballantine & Davies-Colley 2009), consistent with global warming. A warmer climate has been shown to affect productivity in lakes, by changing nutrient availability and by enhancing growth rates of phytoplankton and increasing chlorophyll *a* concentrations, in particular by lakes fed by snow melt (Quayle et al., 2002).

The trophic level index TLI is a useful tool to summarize the trophic state in lakes and to quickly assess changes and trends of eutrophication in lakes over time. However, it must be kept in mind that the TLI is constructed by combining transformations of several variables, which do not necessarily change in the same direction. TLI integrates and summarizes processes that affect water quality but for a deeper and more detailed understanding of the lake ecosystems it will remain necessary to examine the individual variables. There are strong parallels with LakeSPI as an integrating measure which may require closer examination of contributing metrics to identify the nature of changes that occur in lakes.

The most significant finding from this study, broadly consistent with the earlier snapshot report by Sorrell (2006), is that pastoral land use in NZ is associated with eutrophication and ecological deterioration. Furthermore, the condition of some lakes currently in good condition is declining, likely as a result of nutrient enrichment from livestock farming.

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- Gisborne District Council (particularly Paul Murphy).
- Hawke's Bay Regional Council (particularly Brett Stansfield).
- Horizons Manawatu Wanganui Regional Council (particularly Kate McArthur).
- Greater Wellington Regional Council (particularly Alton Perrie and Juliet Milne).
- Marlborough District Council (particularly Fleur Tiernan).
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8. Abbreviations

DO	Dissolved oxygen concentration
LakeSPI	Lake Submerged Plant Index
SOE	State of Environment Report
TLI	Trophic Level Index (from Burns *et al* (2000))
TN	Total nitrogen
TP	Total phosphorus
CHLA	Chlorophyll *a*
SECCHI	Secchi depth transparency
DRP	Dissolved reactive phosphorus
NH4N	Ammoniacal nitrogen
NNN	Oxidized nitrogen, NO_3 and NO_2
COND	Conductivity
SS	Suspended solids
TURB	Turbidity

Councils

ARC	Auckland Regional Council
BOP	Environment Bay of Plenty
ECAN	Environment Canterbury
ES	Environment Southland

EW	Environment Waikato
GWRC	Greater Wellington Regional Council
HBRC	Hawkes Bay Regional Council
HRC	Horizons Manawatu Whanganui Regional Council
NRC	Northland Regional Council
ORC	Otago Regional Council
TRC	Taranaki Regional Council
WCRC	West Coast Regional Council

9. Appendix 1

Appendix 1: Morphological and catchment characteristics of the lakes for which water quality data were collected in 2004-2006 (Sorrell 2006) and in 2005-2009, ordered by TLI in 2005-2009. The percentage change in TLI since 2004-2006 is indicated and does not suggest significance for individual lakes. Percentage annual change (PAC) in the period 2005-2009 is indicated, with significance levels (sign.: ns = not significant, * = < 0.05, ** = <0.01, *** = < 0.001, **** = < 0.0001). Where no PAC is given insufficient data were available to determine trends. All significant PAC's are >2%.

Lake name	Region	Maximum depth (m)	Latitude	Longitude	Altitude (m)	Area (km^2)	Dominant Land cover	Lake Type	TLI mean 2004-2006	TLI mean 2005-2009	Change %	PAC 2005-2009	sign.
Coleridge	Canterbury	200	5767173	2388218	507	36.88	Native	Glacial	1.2	1.3	8.6	21.4%	*
Tekapo	Canterbury	120	5698996	2310979	708	96.59	Alpine	Glacial	2	1.3	-33.1	5.5%	ns
Benmore	Canterbury	120	5634947	2286478	360	75.85	Pasture	Reservoir	1.3	1.3	3.1		
Ohau	Canterbury	129	5658940	2259235	517	59.27	Native	Glacial	1.4	1.4	-0.7		
Pukaki	Canterbury	70	5679850	2283162	494	172.74	Alpine	Glacial	1.4	1.5	9.3		
Sumner	Canterbury	134.5	5833483	2445793	521	13.73	Native	Glacial	1.4	1.6	17.4	16.5%	**
Hawea	Otago	384	5630626	2217057	374	151.77	Native	Glacial	1.7	1.6	-3.1	0.0%	ns
Wakatipu	Otago	380	5561667	2160117	310	298.25	Native	Glacial	2.3	1.9	-15.8		
Taupo	Waikato	162.8	6263510	2761466	375	612.64	Native	Volcanic	2.2	2.1	-5.0	1.6%	ns
Te Anau	Southland	417	5541983	2096331	203	342.97	Native	Glacial	2.5	2.1	-15.9	-8.9%	***
Wanaka	Otago	311	5624063	2201051	277	204.00	Native	Glacial	1.9	2.1	13.0		
Manapouri	Southland	444	5506686	2079928	179	141.78	Native	Glacial	2.4	2.2	-9.9	-4.1%	*
Taharoa	Northland	37	6599239	2569199	70	2.04	Native	Dune	2.5	2.2	-13.5	-6.7%	ns
Dunstan	Otago	30	5569628	2214738	200	26.73	Native	Reservoir	2.1	2.2	3.3	-0.2%	ns
Ida	Canterbury	9	5773663	2391294	680	0.10	Alpine	Glacial	2.2	2.2	-0.1	2.3%	ns
Taylor	Canterbury	40.5	5826358	2447313	588	2.07	Native	Glacial	2.1	2.2	6.7	7.7%	**
Te Kahika	Northland	11	6730838	2510898	15	0.14	Exotic	Dune	3.8	2.3	-40.5		
Rotoma	Bay of Plenty	83	6344716	2824704	313	11.12	Native	Volcanic	2.5	2.4	-4.7	-4.5%	ns
Selfe	Canterbury	30	5773127	2389692	578	0.65	Pasture	Glacial	2.2	2.4	9.2	8.9%	*
Lyndon	Canterbury	28	5766406	2404487	841	0.88	Native	Glacial	2.4	2.5	3.5	8.6%	*
Katrine	Canterbury	28	5831848	2444415	523	0.78	Native	Glacial	2.2	2.5	13.6	9.8%	**
Heron	Canterbury	36.2	5746534	2362643	694	6.95	Native	Glacial	2.3	2.5	9.0	9.0%	**
Pearson	Canterbury	17	5788399	2410832	607	2.02	Native	Glacial	2	2.6	31.5	12.4%	***
Grassmere	Canterbury	15	5793167	2410195	583	0.62	Pasture	Glacial	2.4	2.7	12.5	9.6%	**
Brunner	West Coast	109	5841994	2382724	86	40.61	Native	Glacial	3.3	2.7	-17.4	1.7%	ns
Hawdon	Canterbury	4	5788633	2416383	576	0.35	Pasture	Glacial	2.5	2.7	9.3	6.6%	**
Sarah	Canterbury	6.7	5794662	2410313	578	0.22	Pasture	Glacial	2.6	2.7	5.6	6.5%	*
Tikitapu	Bay of Plenty	27.5	6328765	2801872	418	1.44	Native	Volcanic	3.2	2.8	-13.6	-0.6%	ns
Okataina	Bay of Plenty	78.5	6335922	2809199	311	10.73	Native	Volcanic	3.1	2.8	-10.2	-1.0%	ns
Tarawera	Bay of Plenty	87.5	6327992	2810620	299	41.15	Native	Volcanic	2.9	2.8	-3.9	-1.2%	ns
Kaweka	Hawkes Bay	12.6	6199341	2799781	669	0.09	Native			2.8			
Waikere	Northland	30	6600154	2567597	79	0.30	Pasture	Dune	3.6	2.9	-19.7	-12.7%	****
Alexandrina	Canterbury	30	5693438	2305464	712	6.46	Pasture	Glacial	2.7	2.9	7.9	7.2%	**
Camp	Canterbury	18.9	5730709	2353070	680	0.44	Pasture	Glacial	2.7	2.9	8.5	6.3%	**

Lake name	Region	Maximum depth (m)	Latitude	Longitude	Altitude (m)	Area (km^2)	Dominant Land cover	Lake Type	TLI mean 2004-2006	TLI mean 2005-2009	Change %	PAC 2005-2009	sign.
Tennants	Chathams	4	669650	344400	19	0.50	Pastoral	Peat		3.2		2.0%	ns
Rangitai	Chathams	1.3	674700	363850	2	8.67	Pastoral	Peat		3.2		-0.7%	ns
Te Paki	Northland	2.5	6741125	2492028	94	0.02	Native	Dune		3.2			
Kai-iwi	Northland	16	6598361	2569729	72	0.27	Native	Dune	3.7	3.2	-12.4	-5.9%	*
Okareka	Bay of Plenty	33.5	6331329	2804548	355	3.34	Native	Volcanic	3.4	3.3	-4.1	-0.8%	ns
Rotorangi	Taranaki	60	6187483	2641106	70	6.26	Pastoral	Reservoir		3.4			
Ototoa	Auckland	27.5	6520426	2621349	64	1.07	Native	Dune	3.8	3.4	-11.0		
Clearwater	Canterbury	19	5731997	2352183	668	1.97	Native	Glacial	3.2	3.5	8.7	6.8%	***
Georgina	Canterbury	10	5764587	2393918	545	0.17	Pasture	Glacial	2.9	3.5	20.7	8.7%	ns
Rotokawau, Pouto	Northland	11	6538807	2613517	59	0.26	Exotic	Dune	3.9	3.5	-9.3		
Morehurehu	Northland	14	6728865	2510606	17	0.36	Exotic	Dune	4.1	3.5	-13.7		
Rerewhakaaitu	Bay of Plenty	15.8	6317066	2816346	438	5.17	Pasture	Volcanic	3.5	3.5	1.3	3.9%	***
Maori (front)	Canterbury	shallow	5735390	2363190	630	0.10	Pastoral	Glacial		3.6			
Humuhumu	Northland	14	6540962	2611441	42	1.40	Exotic	Dune	4.1	3.6	-12.4		
Opouahi	Hawkes Bay	24	6221481	2841511	485	0.06	Native			3.7			
Swan	Northland	5.5	6540544	2612829	36	0.17	Exotic	Dune		3.7			
Maori (back)	Canterbury	2.6	5735840	2362066	630	0.10	Native	Glacial		3.7			
Heather	Northland	5.6	6683381	2528513	35	0.08	Pasture	Dune	4.3	3.8	-12.7	1.1%	ns
Marakapia	Chathams	2.5	667150	345550	17	0.36	Pastoral	Peat		3.8			
Waipara/Dead	Northland	10	6735082	2497639	77	0.02	Exotic	Dune	4.2	3.8	-9.4	9.0%	*
Rotokawau, Aupouri	Northland	3.3	6686958	2529655	55	0.15	Exotic	Dune	4.3	3.8	-10.7		
Rotoiti	Bay of Plenty	126	6346199	2810076	279	33.69	Native	Volcanic	4.8	3.9	-19.8	-1.9%	ns
Emily	Canterbury	2.3	5738063	2366774	678	0.19	Pastoral	Glacial		3.9			
Onslow	Otago	9.5	5512083	2246837	684	11.58	Native	Reservoir		3.9			
Rotomahana	Bay of Plenty	125	6320694	2811331	335	9.02	Native	Volcanic	3.9	3.9	1.1	2.2%	*
Tutira	Hawkes Bay	42	6212763	2846091	150	1.70	Native	Landslide		4.0			
Ngatu	Northland	6.5	6685531	2528923	36	0.52	Pasture	Dune	4.1	4.0	-2.5	3.1%	ns
Mokeno	Northland	5.5	6538876	2605741	5	1.59	Exotic	Dune	5	4.0	-19.0		
Coopers Lagoon	Canterbury	3.2	5704533	2455153	1	0.02		Lagoon		4.1		1.6%	ns
Tomarata	Auckland	5	6555045	2658951	23	0.14	Pasture	Dune	4.4	4.1	-7.6		
Ngakapua (North)	Northland	8.2	6686948	2528353	57	0.03	Exotic	Dune	4.5	4.1	-9.2	1.6%	ns
Wainamu	Auckland	15	6478113	2641296	30	0.15	Native	Landslide	4.4	4.1	-6.1		
Waihopo	Northland	3.4	6716204	2514871	35	0.03	Exotic	Dune	4.3	4.2	-3.4	1.3%	ns
Pupuke	Auckland	55	6489737	2668039	0	1.04	Urban	Volcanic	4.3	4.2	-3.4		
Ngakapua (South)	Northland	5.2	6686889	2528576	57	0.06	Exotic	Dune	4.6	4.2	-8.6	-1.3%	ns
Kanono	Northland	15	6537016	2613250	55	0.77	Exotic	Dune	4.2	4.2	0.3		
Rotoroa	Northland	8	6682525	2528712	26	0.28	Pasture	Dune	4.3	4.3	-0.6	2.7%	ns
Kahuparere	Northland	7.5	6536283	2614438	58	0.07	Exotic	Dune	4.5	4.4	-2.4		

Lake name	Region	Maximum depth (m)	Latitude	Longitude	Altitude (m)	Area (km^2)	Dominant Land cover	Lake Type	TLI mean 2004-2006	TLI mean 2005-2009	Change %	PAC 2005-2009	sign.
Waikopiro	Hawkes Bay	0	6211500	2846171	150	0.10	Pastoral			4.4			
Waituna Lagoon	Southland	5	5395486	2172526	1	13.59	Pasture	Lagoon	4.5	4.4	-1.2	6.2%	*
Ngakeketa North	Northland	7	6742798	2488764	55	0.11	Native	Dune	4.9	4.5	-8.9		
Waihola	Otago	2.2	5461436	2283720	4	6.08	Pasture	Riverine	4.3	4.5	4.1	0.1%	ns
Rotoehu	Bay of Plenty	13.5	6347680	2820034	295	7.90	Native	Volcanic	4.5	4.5	0.2	-1.2%	ns
Rotomanuka	Waikato	8.7	6361528	2713710	56	0.14	Pasture	Peat	4.7	4.6	-1.6	0.8%	ns
Rototuna	Northland	5	6549477	2604043	117	0.09	Exotic	Volcanic	4.7	4.6	-1.5		
Rotorua	Bay of Plenty	45	6341883	2797129	280	80.48	Pasture	Volcanic	4.9	4.7	-3.6	-1.3%	ns
Carrot	Northland	3	6686569	2527949	56	0.02	Exotic	Dune	5	4.7	-5.3	-4.1%	*
Karaka	Northland	5	6542655	2603865	3	0.11	Exotic	Dune	4.6	4.8	3.7		
Emma	Canterbury	3	5728437	2357108	657	1.67	Pasture	Glacial	3.9	4.8	22.5	11.6%	***
Rotoroa	Waikato	6	6375789	2710488	37	0.52	Urban	Peat	4.7	4.8	1.8		
Kereta	Auckland	5	6511485	2624910	3	0.24	Pasture	Dune	4.3	4.8	11.7		
Waiparera	Northland	6	6695240	2527412	34	1.09	Exotic	Dune	4.8	4.8	1.0	3.4%	ns
Hayes	Otago	32.9	5572345	2179434	329	2.74	Pasture	Glacial	4	4.9	21.8		
Tuakitoto	Otago	3	5437554	2264835	15	1.32	Pasture	Riverine	5.1	4.9	-3.1	-1.2%	ns
Serpentine East	Waikato	shallow	6358755	2714070	56	0.01	Pastoral	Peat		4.9		-0.1%	ns
Johnson	Otago	27	5569585	2173614	392	0.25	Pasture	Glacial	4.3	5.0	16.4	6.0%	ns
Wairarapa	Wellington	2.5	5996166	2697717	0	77.37	Pasture	Riverine	5.3	5.0	-5.5		
Serpentine North	Waikato	4.4	6358905	2713936	56	0.04	Pasture	Peat	5	5.0	0.7	-0.8%	ns
Kuwakatai	Auckland	19	6518581	2621484	53	0.28	Pasture	Dune	5.5	5.1	-8.2		
Wainui	Northland	11.8	6566357	2590008	32	0.04	Pasture	Dune	5.6	5.1	-9.5		
Waipori	Otago	1	5467048	2286029	0	1.84	Native	Riverine	4.7	5.1	8.6		
Okaro	Bay of Plenty	18	6317113	2806968	423	0.30	Pasture	Volcanic	6	5.2	-12.9	-2.9%	ns
Maratoto	Waikato	7.1	6365957	2712868	62	0.18	Pasture	Peat	5.2	5.4	3.2	-1.9%	ns
Te Wapu	Chathams	0.5	679050	369350	1	0.34	Pastoral	Peat		5.4		1.7%	ns
Wainono Lagoon	Canterbury	3	5610345	2363907	1	3.99	Pasture	Lagoon	5.9	5.7	-3.1	2.0%	ns
Waahi	Waikato	5	6402639	2697913	5	4.45	Pasture	Riverine	6.2	5.7	-7.4	-2.0%	ns
Whakaneke	Northland	shallow	6536507	2605846	5	0.09	Exotic	Dune	6.6	5.9	-10.3		
Spectacle	Auckland	7	6556391	2657343	16	0.44	Pasture	Dune	6.4	6.0	-6.9		
Omapere	Northland	2.6	6650076	2582881	240	11.62	Pastoral	Volcanic		6.1		-7.4%	****
Hakanoa	Waikato	2.5	6403221	2701778	80	0.56	Pasture	Riverine	6.7	6.1	-9.4	-3.6%	*
Horowhenua	Horizons	1.8	6063883	2700697	5	3.04	Pasture	Dune	6.7	6.3	-6.5		
Forsyth	Canterbury	4	5711625	2489581	2	5.59	Pasture	Lagoon	6.5	6.4	-1.4	-3.2%	*
Kapoai	Northland	12	6572652	2585614	37	0.02	Pasture	Dune	6.7	6.5	-3.4		
Huro	Chathams	0.3	657400	348450	1	5.98	Pastoral	Peat		6.5		-0.1%	ns
Whangape	Waikato	3.5	6412806	2691846	5	10.79	Pasture	Riverine	6.8	6.7	-1.3	-2.1%	ns
Ellesmere	Canterbury	2.1	5713381	2468141	2	197.81	Pasture	Beach	6.9	6.9	-0.5	1.1%	ns

Lake name	Region	Maximum depth (m)	Latitude	Longitude	Altitude (m)	Area (km^2)	Dominant Land cover	Lake Type	TLI mean 2004-2006	TLI mean 2005-2009	Change %	PAC 2005-2009	sign.
Rotorua	Canterbury	3	5866690	2557903	25	0.43	Native	Riverine	6.6	6.9	4.7	2.9%	ns
Waikare	Waikato	1.8	6415678	2705039	9	34.37	Pasture	Riverine	7.1	6.9	-2.4	0.7%	ns
Ship Creek	West Coast	3	5708430	2199322	3	0.10	Native		2.7				
Rotokakahi	Bay of Plenty	32	6326415	2800852	386	4.33	Exotic		3				
Poerua	West Coast	7.8	5832585	2386762	95	2.13	Native		3.1				
Lady	West Coast	23	5843961	2393035	111	1.41	Native		3.3				
Mahinapua	West Coast	10	5821329	2339616	14	3.94	Native		3.4				
Pretty	Northland	4.4	6735416	2495491	59	0.07	Exotic		3.5				
Vincent	Southland	5	5393554	2189821	19	0.17	Pasture		3.5				
Wahakari	Northland	12	6727765	2504015	53	0.84	Exotic		3.8				
Ngatuwhetu	Northland	5.1	6735918	2500394	72	0.10	Pasture		4.1				
George	Southland	2	5415464	2114289	10	0.91	Pasture		4.3				
Kihona	Northland	8.3	6730334	2502020	58	0.07	Exotic		4.3				
Wilkie	Otago	3	5397118	2236814	20	0.01	Native		4.4				
Midgeley	Northland	15	6590067	2574881	77	0.03	Pasture		4.5				
Reservoir	Southland	5	5387320	2207988	13	0.36	Pasture		4.5				
Cococola (Rotopokaka)	Northland	3.5	6694458	2545805	2	0.12	Native		4.7				
Jacks	Northland	6.5	6645327	2595284	117	0.16	Pasture		4.7				
Ngakeketa South	Northland	8.7	6742636	2490006	38	0.11	Native		4.7				
Ryan	West Coast	3	5863058	2362490	3	0.03	Pasture		5.1				
Waingata	Northland	7	6538308	2613841	57	0.11	Pasture		5.3				
Tomahawk Lagoon #1	Otago	1.2	5475687	2319164	14	0.19	Pasture		5.4				
Tomahawk Lagoon #2	Otago	1.2	5475623	2319795	15	0.10	Pasture		5.4				
Wairere	Northland	5	6546950	2601783	12	0.11	Exotic		5.6				
Rotokauri	Waikato	4	6380054	2703790	27	0.38	Pasture		6.2				
Ngaroto	Waikato	4	6358441	2711318	37	0.92	Pasture		6.3				
Rotokawau West	Northland	2.5	6703378	2539214	8	0.66	Pasture		6.5				
Waimimiha	Northland	2	6672922	2526359	12	0.10	Pasture		6.5				
Waiporohita	Northland	3	6699999	2542715	14	0.07	Pasture		6.6				
Rotokawau East	Northland	2.5	6703212	2540157	8	0.24	Pasture		6.9				
Bason Reserve	Horizons	shallow	6145409	2676840	51								
Dudding	Horizons	11.9	6120295	2704402	86	0.08	Pastoral	Dune					
Papaitonga	Horizons	6.8	6060075	2698200	17	0.52	Pastoral	Dune					
Pauri	Horizons	7.9	6134239	2689410	46	0.19	Pastoral	Dune					
Virginia	Horizons	shallow	6141544	2683857	57	0.07	Urban						
Westmere	Horizons	shallow	6143678	2680964	95	0.08	Pastoral						
Wiritoa	Horizons	19.5	6134659	2688598	44	0.22	Pastoral	Dune					

Notes: Latitude and longitude in New Zealand map grid units. Land cover is dominant catchment land use type mapped from LCDB2.
TLI is only shown for those lakes where TN, TP and chlorophyll a concentration data were available.