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Lake Water Quality in New Zealand

**Status in 2006
and recent trends 1990–2006**

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Executive summary

There has been a large increase in the number of lakes being monitored in New Zealand in recent years, allowing a comprehensive comparison of water quality across land-use types, lake types and regions. This report summarises the current status of lake water quality in New Zealand, based on data from 121 lakes. No previous assessment of lake water quality has involved so many lakes, or incorporated data from lakes varying so widely in their water quality.

Data from lake water quality monitoring programmes of 10 regional councils and recent research data from NIWA and university research programmes were used to assess the current state (based on 2003–2006 data) and trends (from 1997 to 2006) in water quality in lakes throughout New Zealand. Water quality data were used to prepare a national picture of lake condition, and differences in condition were related to four land-cover classes: alpine, native forest/scrub, exotic forest and pasture. Differences in water quality between land-use types were also assessed using a recently developed lake classification scheme that allows the effects of lake morphology (size and depth) and climate to be identified. The range of parameters assessed included total nitrogen, total phosphorus, chlorophyll *a*, Secchi depth, ammonium, nitrate+nitrite, dissolved reactive phosphorus, suspended solids, and temperature. Two indices of water quality and ecological condition were used: the Trophic Level Index (TLI) method, based on lake water quality monitoring results, and the LakeSPI index, based on the depth and composition of the submerged aquatic plant community.

Water quality was found to be strongly correlated with land-cover classes, especially in comparing native vs pasture classes. Median values of total nitrogen, total phosphorus and chlorophyll *a* were four to six times higher in the pasture classes than in the native class. Water quality was also most variable within the pasture class, with many more extreme high values in this class than in the native or exotic forest classes. High exotic forest cover was usually associated with high phosphorus concentrations, but less frequently with high nitrogen concentrations.

Secchi depth data were lacking in many of the records, but those available supported the other data, with median values of 6.2 m in the native class, 2.7 m in the exotic forest class, and 1.2 m in the pasture class. Secchi depth data included many extreme high values in the native class, and extreme lows (< 1.0 m) in the pasture class. Values for ammonium and dissolved reactive phosphorus were also elevated in the pasture and exotic classes, as was conductivity and, to a lesser extent, turbidity. Nitrate-nitrite was low in almost all lakes.

Water quality was very high in the alpine class. TLI values indicated that alpine lakes were predominantly microtrophic or oligotrophic. TLI values for the other three categories varied depending on the proportions of land-cover classes: median values were oligotrophic where the native class predominated, and eutrophic where either the exotic forest or pasture classes predominated. All but two of the 18 supertrophic and hypertrophic lakes in the data set were in the pasture class.

The broad national picture is of high water quality in deep lakes at high altitude and in unmodified catchments, and of lower water quality in modified catchments, especially in small, shallow and warm lakes. Although lake water quality was degraded in both exotic forest and pasture land catchments, pasture use was associated with the worst water quality, most notably in the cases of extreme deterioration (supertrophic and hypertrophic lakes).

A regression tree analysis that related water quality to climate, geography, catchment land cover and lake morphometry (eg, depth, area) produced seven categories of lake water quality in different environments, as shown in the following table.

Group	Number of lakes in data set	Environment description	Water quality	Examples
1	26	Very cold climates	Excellent (all microtrophic or oligotrophic)	Wanaka, Sumner, Te Anau, Tekapo
2	21	Cold winters but milder mean annual temperatures	Good (mostly oligotrophic and mesotrophic)	Rotoma, Tikitapu, Brunner, Lady
3	10	Mild climates, > c. 50% native catchment cover	Good (some oligotrophic, most mesotrophic)	Kai-iwi, Mahinapua, Ototoa
4	7	Mild climate, native and pasture cover are both < c. 50%, far northern	All very high TP, mostly high TN, but very low chl a	A small subset of far north (Aupori Peninsula) lakes
5	25	Mild climate, native and pasture cover are both < c. 50%	Poor (mostly eutrophic and some supertrophic)	Rotorua (Bay of Plenty), Waiparera, Tomarata, Rotokawau
6	20	Mild climate, > 50% pasture cover, lake area < 0.60 km ²	Very poor (mostly supertrophic)	Tomahawk Lagoon, Serpentine, many Northland lakes
7	12	Mild climate, > 50% pasture cover, lake area > 0.60 km ²	Extremely poor (all hypertrophic)	Horowhenua, Ellesmere, Whangape, Ngaroto

Extrapolation of these lake environment categories to the nationwide database of 3,820 lakes suggests that approximately 60% of New Zealand lakes are still likely to have excellent or very good water quality; these are lakes in cold regions with high native and low pasture cover. However, approximately 30% of lakes are likely to have very poor to extremely poor water quality. Lowland lakes are especially likely to have poor water quality.

Comparison of the water quality data with LakeSPI aquatic plant data showed strong decreases in the depth of plant colonisation with decreasing water quality and decreasing native catchment cover, consistent with lower water clarity and light penetration for plant growth. Water quality and land use did not correlate with native plant species diversity and numbers of introduced weed species, which appear to be driven by other pressures such as recreational boating activity and water-level fluctuations.

Recent trends over the last 10 to 15 years could be identified from 49 lakes that have had monitoring programmes in place for more than three years. Although most of these lakes are showing no detectable change, many have already become supertrophic and hypertrophic, so that additional nutrient run-off is not causing increased chlorophyll *a* and decreased clarity because algal growth is already nutrient-saturated. Others not showing trends include most large, deep lakes and lakes in regions with high native cover. Most of the lakes showing deterioration were North Island lakes at low altitudes. However, an encouraging feature of the trend analysis was that some pasture lakes that have long-term catchment management plans in place, involving actions such as restoration of marginal wetlands and riparian retirement of grazing activity, are showing probable improvement.

1 Introduction

New Zealand has a wide variety of lakes, which provide a range of biodiversity, water supply, recreational, aesthetic and food resource values. They are an important part of our clean, green image and economy, contributing to hydropower, tourism and agricultural industries. Although New Zealand lakes vary considerably in their natural water chemistry, colour, clarity and productivity (and there is historical evidence that some were naturally eutrophic¹), land development during the 20th century is known to have significantly altered their character.

Concerns about the condition and water quality of New Zealand lakes are not new. Agriculture, industry point sources, urbanisation and forestry have all been linked to environmental degradation in lakes. Extensive research on lake functioning from the 1960s to 1980s provided a general understanding of the nature of nutrient limitation in different lake types, how productivity changes with change in nutrient input, and how degradation is related to catchment land use. Much of this information was summarised in the 1987 *Lake Managers' Handbook* (Vant, 1987) and other contemporary reviews (Viner, 1987).

More recently, tools such as the Trophic Level Index (TLI) and Lake Submerged Plant Indicators (LakeSPI) have been developed to characterise the degree of nutrient enrichment of a water body (eutrophication) more accurately, and to provide statistically valid methods for identifying degradation (Burns et al, 2000; Clayton and Edwards, 2006). Reviews of the status of New Zealand lakes were carried out in 1986 (Livingston et al, 1986a; 1986b) and 1998 (Burns and Rutherford, 1998), and it is now timely to review the available data. Improved mapping, GIS (geographic information system) and environmental classification tools have been developed in the last 10 years that allow a more comprehensive assessment of lakes and can improve the accuracy of interpretations of relationships between land use, lake characteristics and water quality.

The aim of this report is to provide an overview of the current status and recent trends in lake water quality in New Zealand. We have used water quality data from regional council state of the environment monitoring programmes, from recent lake research programmes by NIWA and universities, and submerged aquatic plant data collected by councils and NIWA for LakeSPI analysis. The principal aim of the analysis is to establish the water quality state of lakes in relation to different land-cover classes and human impacts. This has been interpreted in relation to those differences in lake morphology and mixing patterns that control responses and susceptibility to nutrient enrichment. It incorporates a recently developed lake environment classification that categorises lakes based on climatic and physical characteristics that strongly affect their hydrology, chemistry and biological conditions.

This report is one of two linked projects commissioned by the Ministry for the Environment to provide a national snapshot of lake water quality. Ministry for the Environment (2006) has already reported on and analysed the monitoring programmes carried out by councils, and identified patterns in trophic level and lake condition from the council data. In the present report we assume knowledge of the Ministry for the Environment (2006) report and do not repeat its contents. The important conclusions from the previous Ministry for the Environment report and their implications for our analysis are as follows.

¹ See Appendix 1 for a glossary of important limnological terminology.

- *Most of the lake water quality monitoring is occurring in relatively large, deep lakes, due to public interest in these lakes.* As a result, lake monitoring is not representative of the national lake resource, in which there are many more small, shallow lakes than large, deep lakes. However, enough small lakes are being monitored to understand their condition, and the lakes monitored span a range of sizes that provides a valid comparison of how size affects condition.
- *The lakes monitored span almost the full range of trophic states from microtrophic to hypertrophic (see Table 4 in section 2.2.2 for definitions of trophic level classes).* North Island lakes show higher trophic levels than South Island lakes, and a larger deterioration over time (as detected by the TLI) than South Island lakes. Trophic level appears to be higher (ie, water is more nutrient enriched) in developed catchments with human pressures than in native catchments. There are some recent apparent improvements in water quality in some South Island lakes, which appear to be primarily due to short-term climatic fluctuations. In general, trend analysis should be based on a minimum of three years' data to avoid incorrectly attributing short-term variation to human pressures. Condition recorded by LakeSPI suggests an overall deterioration in the North Island subset for which LakeSPI data are available.
- *Shallow lakes (≤ 10 m) have much poorer water quality (higher trophic levels) than deep lakes (> 10 m).* Shallow lakes have lower volume than deeper lakes, and will respond more rapidly to catchment land use because there is less dilution, and less contact between water and sediments. Although shallow lakes tend to be naturally more productive than deep lakes, New Zealand has a large number of naturally oligotrophic shallow lakes (especially dune lakes), and not all of the shallow eutrophic, supertrophic and hypertrophic lakes in the data set would have been enriched in their natural condition. In general, the ecological functioning of shallow lakes has received much less research effort than that of deep lakes in New Zealand, and they are not so well understood. Differences in trophic state between different types of lakes (dune lakes, volcanic lakes, glacial lakes, etc.) are likely to be related more directly to their morphometry and catchment land use than their geological origin *per se*. Dune lakes were strongly represented in the more eutrophic categories because most dune lakes are shallow and have developed catchments, whereas most glacial lakes were low in trophic level because most glacial lakes are deep and have less modified catchments. Otherwise, there was little evidence of systematic differences in trophic levels between different lake types.

2 Methods

2.1 Lake database and classification

For this analysis we have used a GIS-based national database of 3,820 New Zealand lakes greater than 1 ha in area, delineated from the NZMS 260 1:50,000 topographic map series. These lakes include over 98% of the total lake area of New Zealand according to the latest Land Information New Zealand (LINZ) database. Water quality data are only available for a small fraction of these lakes, but their ecological character can be classified according to the major limnological variables that drive water quality (eg, mixing regime, morphometry, nutrient inputs), allowing extrapolation to other lakes.

We have used two classification approaches to explore differences in lake condition among different lake types. The traditional method of lake classification in New Zealand and elsewhere is based on mode of geological formation, originally developed by Hutchinson (1957), and adapted for New Zealand by Irwin (1975). This method produces eight lake categories (see Table 1), plus sub-categories and combinations of these.

NIWA has recently developed a lake environmental classification scheme for the Department of Conservation that incorporates these classes, together with other environmental factors that control lake ecosystems (Snelder, 2006), such as climate, catchment type, size and shape, all of which are known to influence water quality and ecosystem structure. These factors are arranged hierarchically from those likely to be important at a national scale (eg, climate) to those likely to be important locally (eg, soil type). The geological emphasis of the Hutchinson and Irwin classifications is captured in factors such as soil type and lake shoreline development. The environmental classes produced from this approach allow condition to be compared between groups of lakes that differ in ecological character at a range of spatial scales. The classification can group lakes according to their natural (pre-European settlement) character or according to modern land-use classes. This method results in seven primary classes of lakes (see Table 2) distinguished at the national scale, with sub-categories of each at more regional scales. Table 2 emphasises that most lakes in New Zealand are small. Note that the Snelder (2006) classification scheme is still provisional and likely to be refined further.

Table 1: Classification of New Zealand lakes* based on mode of geological origin, following Irwin (1975)

Mode of geological origin	North Island	South Island
Glacial	0	291
Riverine	67	54
Wind	106	13
Artificial	34	31
Landslide	18	20
Barrier bar	14	18
Volcanic	30	0
Others	31	49

* Includes only lakes with at least one axis > 0.5 km (a total of 776 lakes).

Table 2: Classification of New Zealand lakes* based on the lake environmental classification scheme of Snelder (2006)

Class of primary classification	Number of lakes	Description
1	1,581	Small lakes mainly in warm (northern) locations
2	960	Small central lakes
3	1,074	Small lakes in cool (southern) locations
4	75	Medium-sized lakes in cool locations
5	94	Medium-sized lakes in warm locations
6	4	Large, shallow lakes in warm locations
7	32	Large, deep lakes

* Includes all lakes > 1 ha in area (a total of 3,820 lakes).

Differences in depth stratification patterns are central to understanding lake productivity and its responses to human activities. Lakes that are deep enough to undergo full seasonal stratification (monomictic lakes) are almost exclusively in classes 4, 5 and 7. The few large, coastal lakes in class 6 are too shallow and have too great a fetch to stratify seasonally, and most of the small lakes in classes 1 to 3 are too small for seasonal stratification. However, brief intermittent stratification (polymixis) is common in these lakes, sometimes diurnally or sometimes irregularly, depending on solar radiation, wind and air temperature.

2.2 Water quality data and land-use classification

2.2.1 Data collection

We obtained lake water quality data from regional councils, local authorities and research institutes for all lake sites that have been monitored over the last 10 years, and in some cases received data going back as far as 1990. All data were provided with GPS (global positioning system) locations of collection sites, which we used to link data to our lake database. Errors in GPS readings were corrected algorithmically to ensure all sites were correctly located. The water quality data collected are shown in Table 3.

Table 3: Water quality data collected from regional councils, local authorities and research institutes

TLI parameters (requested as a minimum)	Additional parameters collected where available
Total nitrogen (TN)	Inorganic nitrogen forms (NH ₄ -N and NO ₃ -N)
Total phosphorus (TP)	Dissolved reactive phosphorus (DRP)
Secchi depth (Z _{SD}),	Suspended solids (SS)
Chlorophyll-a (chl _a)	Dissolved organic carbon (DOC)
	pH
	Temperature
	Conductivity
	Dissolved oxygen (DO)

Nutrient concentrations below detection limits were replaced with values equal to half the detection limit. Measurements that were clearly erroneous were deleted, and in some cases there were errors in units of concentrations that could be corrected by comparison with other data. Data sets varied widely with regard to the inclusion of parameters, and also in the number of data and numbers of missing values for each parameter. As a result, the total number of data points varied widely among parameters.

Sufficient data were available to characterise recent water quality and make statistical comparisons for 121 lakes from 10 regions. This is a much greater number of lakes than previous comparisons, which have usually involved fewer than 20 lakes, and reflects the increase in lake monitoring carried out by councils in recent years. Of the 121 lakes, only 49 had data sets of sufficient duration and number of data points to calculate trends following Burns et al (2000). We have therefore taken two approaches:

- a nationwide analysis of the current condition or state of New Zealand lakes based on the 121 lakes
- trend analysis on data from the 49 lakes.

To carry out a robust trend analysis, our minimum requirements were a three-year data set and at least 15 time points to fit linear regressions. For the nationwide snapshot of condition, we took significant differences in condition between land use and lake morphology identified from the 121 lakes; and then used the GIS database to extrapolate to the 3,820 lakes. Morphological and catchment characteristics of these lakes are shown in Appendix 2.

2.2.2 Trophic Level Index (TLI)

We compared water quality using raw data for the various individual parameters and using the TLI methodology. The TLI method logarithmically transforms TN, TP, Z_{SD} and *chl*_a data to give a trophic level score for each parameter on the same scale. The formulae for these four component indices (TL_n, TL_p, TL_s and TL_c) are:

- $TL_n = -3.61 + 3.01 \log_{10} (TN)$
- $TL_p = 0.218 + 2.92 \log_{10} (TP)$
- $TL_s = 5.10 + 2.27 \log_{10} (1/Z_{SD} - 1/40)$
- $TL_c = 2.22 + 2.54 \log_{10} (Chl_a)$.

The method then averages the four component scores into an index of trophic condition, the TLI. Trophic state classes are defined based on the TLI range (see Table 4).

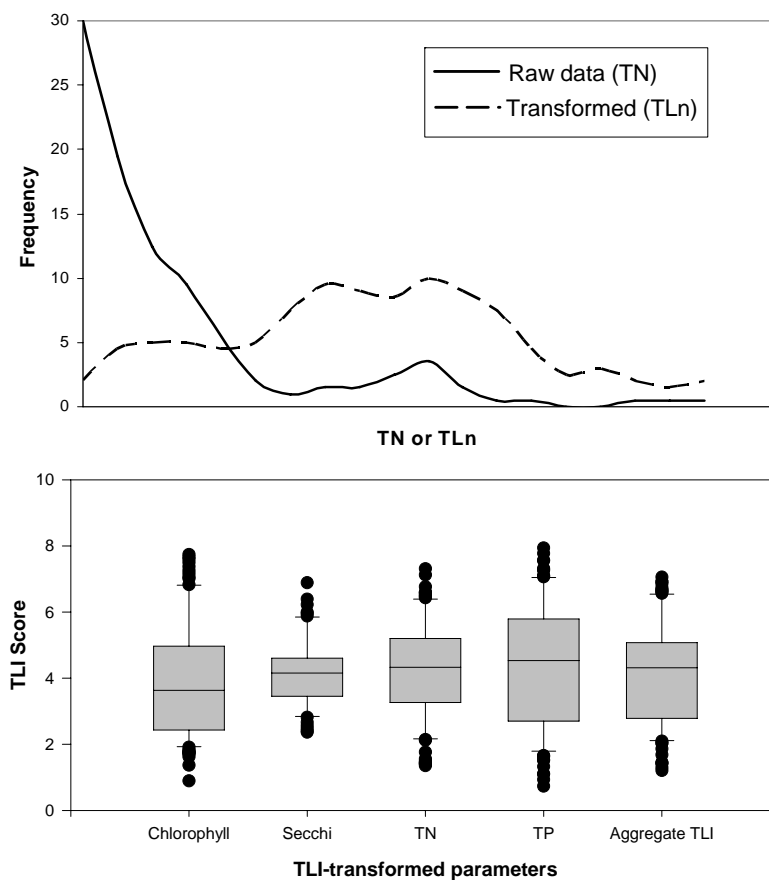
Table 4: Definition of seven trophic states based on range in average Trophic Level Index (TLI), and corresponding nutrient enrichment descriptions*

TLI	Trophic state	Nutrient enrichment description
< 1	Ultra-microtrophic	Practically pure
1–2	Microtrophic	Very low
2–3	Oligotrophic	Low
3–4	Mesotrophic	Medium
4–5	Eutrophic	High
5–6	Supertrophic	Very high
> 6	Hypertrophic	Saturated

* As described by Burns et al (2000).

The raw TN, TP, Z_{SD} and *chl a* data were highly skewed, but the log-transformation ensured that TL_n, TL_p, TL_s and TL_c were close to normal distributions, enabling statistical comparisons. Figure 1 compares histograms of the raw data and transformed data for TN as an example, with the raw data being highly skewed (many low values), compared with the normally distributed TL_n data. Figure 1 also shows the normal distributions of all four TLI components and the aggregate TLI.

Figure 1: Upper: Comparison of frequency distributions of raw TN data and transformed TL_n data for all lakes. Lower: Box and whisker plots for distributions of TLI components and aggregate TLI for all lakes



Notes: Horizontal lines within boxes show median values, boxes show 25–75% data ranges, whiskers show 5–95% ranges, and points are outliers outside the 5–95% ranges.

The average TLI and its components were used in parametric statistical tests. Untransformed values are used at all other times.

2.2.3 Land cover/use

Land cover was determined from the latest New Zealand land-cover database (LCDB2, 2001–2002). The LCDB2 classes were grouped to form five land categories that covered almost all land in lake catchments throughout the database:

- alpine
- native forest and scrub (hereafter termed native)
- pasture
- exotic forest
- urban.

We then took two approaches to looking at relationships of catchment type to water quality.

First, we took a broad overview by associating lakes with the *predominant* land use in their catchment. The rule applied to LCDB2 was that the predominant land use was the largest single land-cover class in the catchment. This approach has limitations. For example, dominant land use may not be the most important factor affecting water quality in lakes where point sources are more important than diffuse sources. An example of this is Lake Rotoiti (Bay of Plenty), where the input from the Ohau Channel (draining Lake Rotorua) has a large effect on trophic state, even though native is the largest single land cover for this lake's catchment (unless the Lake Rotorua catchment is included as part of the Rotoiti catchment). Lakes Horowhenua and Rotorua (Bay of Plenty) are other examples of lakes with a history of significant point source inputs. However, relatively few New Zealand lakes have large point source inputs, and these outliers were easily identified and are discussed separately. The trophic state of the large majority of New Zealand lakes is driven by diffuse catchment inputs that can be explained from land-use patterns.

Another limitation of simple dominance rules is that some land uses may have a proportionately greater influence on water quality than others. For example, urban land use often has very dramatic effects on water quality even if only present in small amounts. This may also differ in different soil types: a given land use may contribute greater nutrient run-off in porous soils such as sand and pumice than in other less porous soils. Also, land-cover classes such as 'pasture' will include agricultural land with a range of livestock species, stocking densities and management practices. In many regions councils have specific land-use information to allow closer examination of land-use practices and water quality. However, we found that the dominant land use identified from LCDB2 data was adequate to provide a useful picture of broad land-use effects.

Second, we examined land-use relationships by plotting TLI values and individual water quality parameters against the proportion of the catchment in different land-use types, to complement the analysis based on simple dominance. This approach allowed more detailed examination of interactions between land use, lake morphology and climate.

2.3 LakeSPI

All LakeSPI data collected by NIWA were incorporated into the database and linked to the appropriate lake ID and water quality set. LakeSPI is an aggregate score based on three parameters:

- plant colonisation depth (defined as depth where plant cover is < 10%)
- native condition index (higher score for greater species diversity)
- invasive condition index (lower score for more species and greater invasion).

There were 39 lakes for which we had both TLI and LakeSPI data, all in Bay of Plenty, Waikato and Northland.

2.4 Data analysis

Of the parameters provided in the data sets, eight water quality parameters (TN, TP, Z_{SD} , *chl_a*, NO_3-N , NH_4-N , conductivity and pH) were available in sufficient detail to allow comparisons between regions and land-cover types, and were used in the state analysis. TLI values were calculated from the four TLI variables (TN, TP, Z_{SD} , *chl_a*) according to the TLI methodology (Burns et al, 2000), but these variables were also examined individually because their individual responses can differ with different land-use impacts. The three LakeSPI parameters and their aggregate LakeSPI score were treated similarly. Current values for water quality parameters used in the state analysis were calculated as de-seasonalised averages of 2004–2006 data.

Seventy-five lakes had only three of the four TLI parameters (TN, TP and *chl_a*). However, we found that the average TLI in those lakes for which we had all four parameters correlated moderately well with the average TLI based on TN, TP and *chl_a* alone. Accordingly, we used the three-parameter average TLI when Z_{SD} was not available. Burns et al (2000) also provide evidence that a three-parameter TLI is adequate for lake characterisation in many cases.

Our statistical analysis of the factors driving lake water quality was based on the classification and regression tree method (De'ath and Fabricius, 2000). This is a relatively simple regression method that can deal very robustly with non-linear relationships and data sets with many missing values. Briefly, tree analysis carries out iterative calculations and generates regression trees that identify the independent factors (eg, lake size, shape and location, catchment land use) that are most important in driving the dependent variables (ie, water quality parameters). It then presents them visually as a tree diagram, dividing lakes into groups differing in water quality relating to the important variables. For this analysis we generated regression trees using TLI indices for TN, TP, *chl_a* (121 lakes), and alternative trees using TLI indices for all four parameters where these were available (75 lakes). The tree accepted is the smallest one within one standard error.

For trend analysis we took two approaches. For the 49 lakes that have monitoring data long enough for accurate trend analysis, we applied the percent annual change (PAC) methodology as described by Burns et al (2000). Data for these lakes are from post-1990, and include continuous 1990–2006 records in some regions, 1995–2006 records in some regions, and sporadic monitoring in the 1990–2006 period in others. It should be stressed that Burns et al (2000) recommended three-year running averages as a time scale suitable for validly identifying trends. Spurious significant trends, or significant trends related to short-term natural changes rather than long-term pressures, can often arise when shorter records are used, especially in oligotrophic lakes, where a small change in water quality can give a high PAC value.

The Canterbury high-country lakes in the data set are a good example. Their monitoring only began recently (December 2004), and shows decreases in TN, TP and chl a over that time. These apparent improvements in what were already near-pristine lakes with little human pressure appear to be related to recent drought conditions in Canterbury and reduced inflows, which decreased nutrient inputs. Such lakes demonstrate that fluctuations in water quality do occur independently of human effects, and emphasise the need to use appropriate long-term data sets for identifying human impacts.

To provide a view of longer-term changes, we also made simple comparisons of the current state against two time points at which the state had previously been described for a range of lakes. White (1983) used 27 lakes ranging from oligotrophic to eutrophic condition in his classic study of the nature of nutrient limitation in New Zealand lakes. We were able to access recent data for 16 of these, and we plotted 1983 values for TN, TP and chl a from these lakes against 2004–06 averages. Early Z_{SD} values were too variable to make comparisons. Burns and Rutherford (1998) monitored 26 lakes over 1992–1996 in developing the New Zealand lake monitoring programme, of which 18 had recent monitoring data for comparison. This exercise allowed a broad-scale comparison of current 2006 lake status against two time points (1983 and 1996), albeit with a different set of lakes in each comparison.

3 Results and discussion

3.1 Current water quality and trophic states

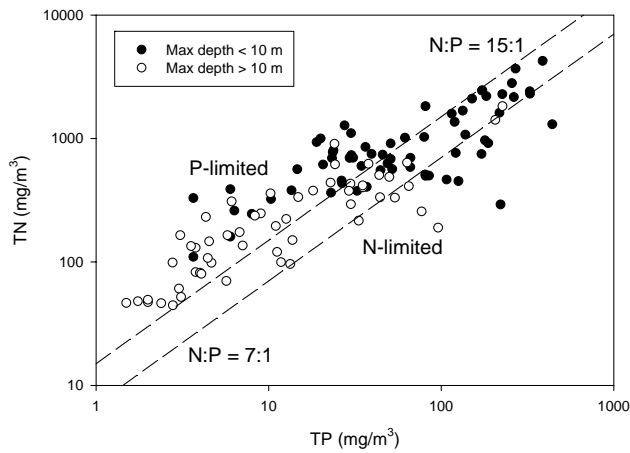
Lakes in the data set ranged from microtrophic to hypertrophic. Approximately 60% of the lakes were in eutrophic or worse condition, and most of these lakes were in the North Island. The lakes monitored therefore cover a wide range of trophic states and are useful for identifying factors responsible for eutrophication. Ministry for the Environment (2006) discusses regional variation in water quality in more detail. This section considers the nature of nutrient limitation and relative concentrations of nutrients, which are critical to the identification of deterioration in water quality and lake condition.

Figure 2 shows that the lakes included a wide range of nitrogen to phosphorous (N:P) ratios and concentrations, consistent with the wide range in N and P limitation states for algal growth found previously for New Zealand lakes (eg, White, 1983). The dashed lines in Figure 2 are for N:P ratios of 7:1 and 15:1, which are commonly used to demarcate nitrogen-limited lakes ($N:P < 7:1$) and phosphorus-limited lakes ($N:P > 15:1$). It confirms that New Zealand has many N-limited lakes and many P-limited lakes, and also lakes where the N:P ratio is between 7:1 and 15:1; ie, in the range where the relative supply of the two nutrients is within the optimal range for balanced algal growth. In these lakes, either nutrient may be limiting or both may limit at different times, especially when concentrations of both are low. When concentrations of both nutrients are very high, algal growth is probably unlimited by nutrients and is only limited by light attenuation.

Another feature of Figure 2 is confirmation that shallow lakes usually have higher concentrations of N and P than deeper lakes, as discussed in the Introduction. The use of 10 m depth as the demarcation between shallow and deep in this exercise is because lakes less than 10 m deep are likely to be polymictic (ie, too shallow to undergo prolonged summer stratification and instead undergo repeated periods of brief stratification and mixing). Lakes > 10 m depth are deep enough to be potentially monomictic (develop summer stratification).

Figure 3 plots *chl a* values from the data set against TN and TP. It shows the strong relationship between nutrient concentrations (both N and P) and phytoplankton biomass in the lakes. Of particular interest is how these relationships change (in slope) at approximately the oligotrophic–mesotrophic boundary ($TN = 100 \text{ mg/m}^3$; $TP = 10 \text{ mg/m}^3$) on the nutrient axes, which suggests that these may be critical values for TN and TP that can be defined for lake management. Another feature of Figure 3 is the many lakes with low *chl a* values at high TP values. Some of these are nitrogen-limited lakes, but some are tannin-stained lakes where algal growth is light-limited or the P is bound in non-biologically available organic forms.

Figure 2: Relationship between total phosphorus (TP) and total nitrogen (TN) for shallow lakes (≤ 10 m maximum depth) and deep lakes (> 10 m maximum depth)



Note: Dashed lines demarcate N:P ratios of 7:1 (below which algal growth is N-limited) and 15:1 (above which algal growth is P-limited). When both are high, growth is probably not nutrient-limited.

Figure 3: Relationship of total nitrogen (TN) and total phosphorus (TP) to chlorophyll a (chl_a) for shallow lakes (maximum depth ≤ 10 m) and deep lakes (maximum depth > 10 m)

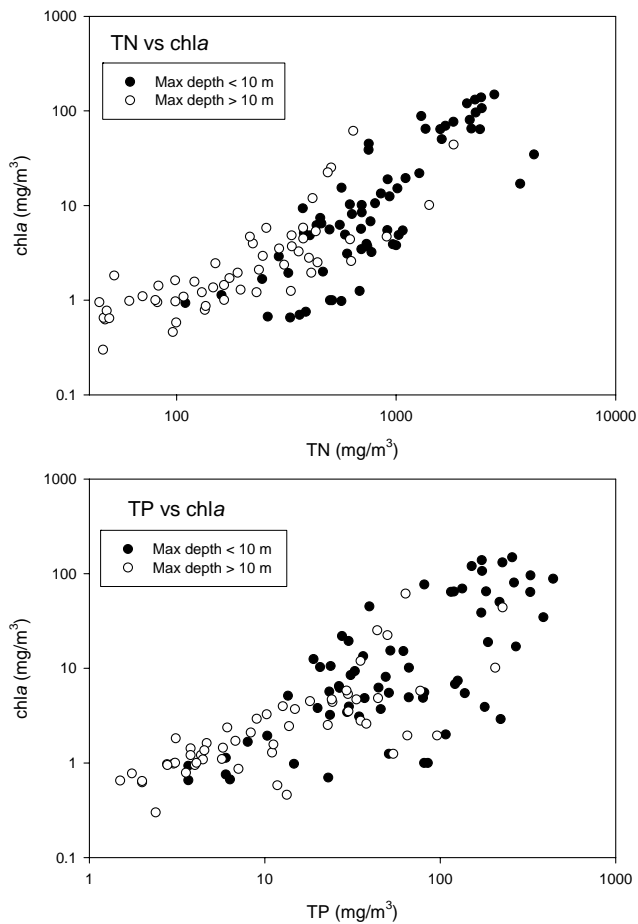
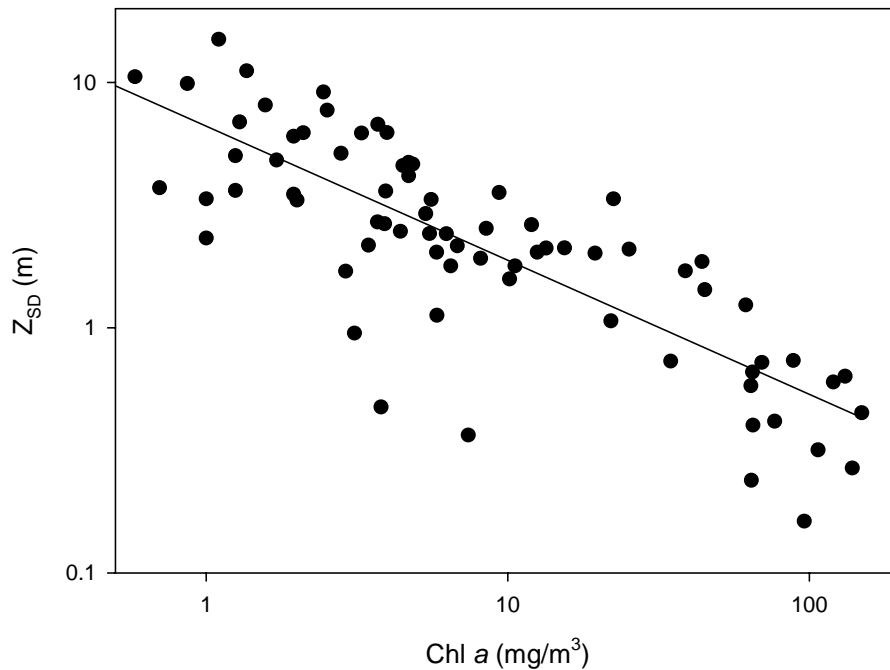


Figure 4 shows that there is a logarithmic relationship between Z_{SD} and $chl a$ (ie, phytoplankton biomass). Hence, most of the decline in Z_{SD} with $chl a$ occurs at $chl a$ values $< 20 \text{ mg/m}^3$; above this value the effect of $chl a$ on Z_{SD} is small because Z_{SD} is already very low. It also shows that $chl a$ is not the only factor controlling Z_{SD} . Natural factors such as dissolved organic carbon (eg, in beech forest catchments) and glacial flour (sediment) contribute to cases of low Z_{SD} values (ie, low clarity) at low $chl a$, and anthropogenic suspended sediments can also explain low clarity values (Vant and Davies-Colley, 1984; Schwarz et al, 2000).

Figure 4: Relationship of Z_{SD} to chlorophyll a ($chl a$) for all lakes ($r^2 = 0.67$)



Note: logarithmic axes are used.

Summary of nutrient relationships

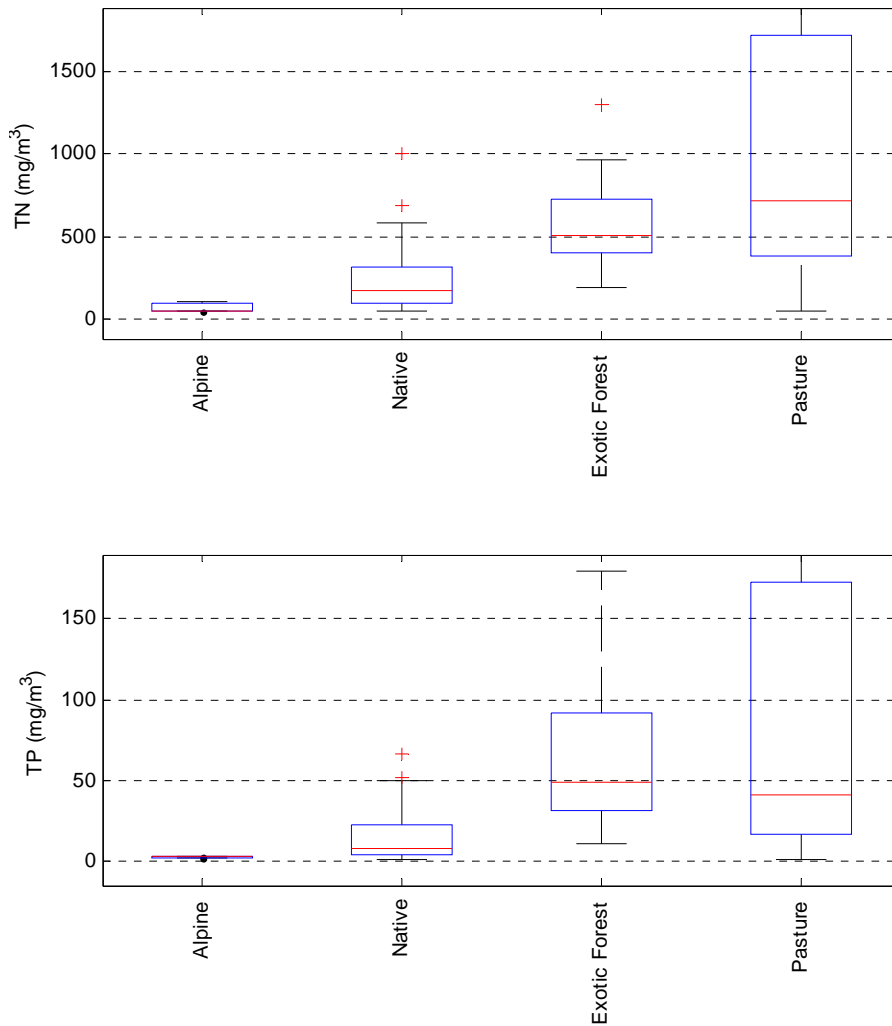
- The lakes in the data set span the full range of possible water qualities, from microtrophic (almost pristine) to hypertrophic (saturated with nutrients), and hence provide a good range for developing statistical relationships (see following sections).
- There are examples of both nitrogen limitation and phosphorus limitation of algal growth in the lakes, and lakes where nutrient concentrations are very high and probably saturating for algal growth. Nutrient concentrations are higher in shallow lakes than in deep lakes.
- There is little increase in algal biomass over the range of N and P concentrations found in oligotrophic lakes, but algal biomass increases logarithmically once nutrients rise into the mesotrophic range.

3.2 Land-cover relationships

Catchment descriptions allocated 55 lakes to the predominantly pasture class, 39 to the native class, 22 to exotic forest, and three to the alpine class. Only two lakes (Lake Pupuke and Hamilton Lake) were allocated to predominantly urban catchments, and this class was therefore excluded from figures comparing land use (Figures 5 to 8). Differences in TN, TP, Z_{SD} and *chl_a* between the land-cover classes (Figure 5) were highly significant. TN, TP and *chl_a* were all extremely low in the alpine class. Median values for TN, TP and *chl_a* were all lower for the native class than in the exotic and pasture classes. Although the median values of TN, TP and *chl_a* for the pasture class were similar to the exotic class, there were many more extreme high values in the pasture class than in other classes, and all of the lakes with very high concentrations of TN, TP and *chl_a* were in the pasture class. Z_{SD} was also affected by land use, being highest (ie, clearest water) in the native class, followed by exotic, and then pasture. (Note that there were no Z_{SD} data for the alpine class.)

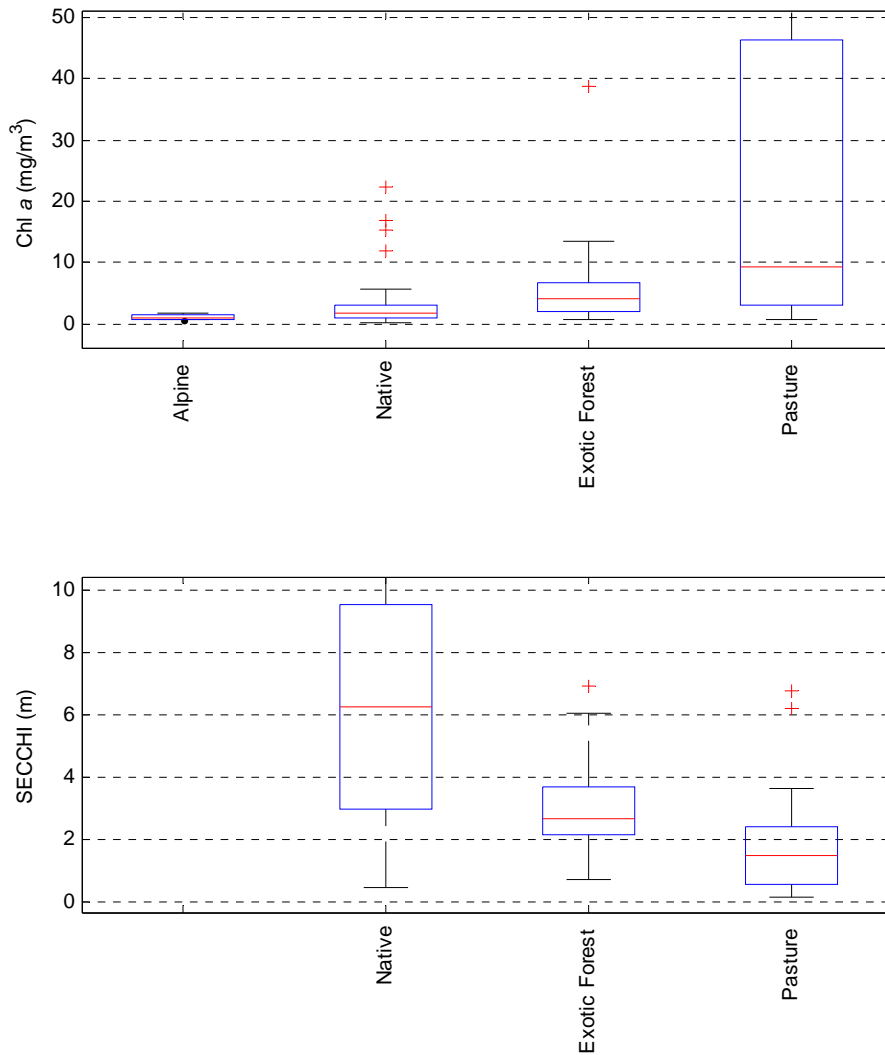
The average TLI statistics derived from these parameters also differed between land-use classes (Figure 6). Median TLI values were highest for the pasture and exotic classes (both eutrophic), with the extreme values (most supertrophic and all hypertrophic lakes) in the pasture class. Native category lakes were predominantly oligotrophic or mesotrophic, and alpine lakes had the lowest TLI values.

Figure 5a: Box-and-whisker plots showing differences in total nitrogen (TN) and total phosphorus (TP) in four classes of predominant land cover (alpine, native, exotic forest and pasture)



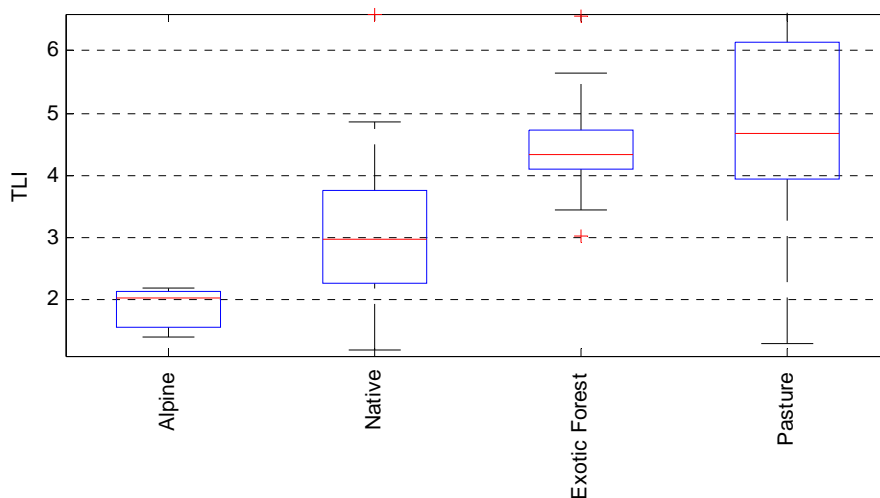
Notes: Horizontal lines within boxes show median values, boxes show 25–75% data ranges, whiskers show 5–95% ranges, and pluses show outliers outside the 5–95% ranges.

Figure 5b: Box-and-whisker plots showing differences in chlorophyll a (chl_a) and Secchi depth in four classes of predominant land cover (alpine, native, exotic forest and pasture)



Notes: Horizontal lines within boxes show median values, boxes show 25–75% data ranges, whiskers show 5–95% ranges, and pluses outliers outside the 5–95% ranges. No Secchi depth data were available for the alpine lakes.

Figure 6: Box-and-whisker plots comparing TLI across the four land cover classes (alpine, native, exotic forest, and pasture)

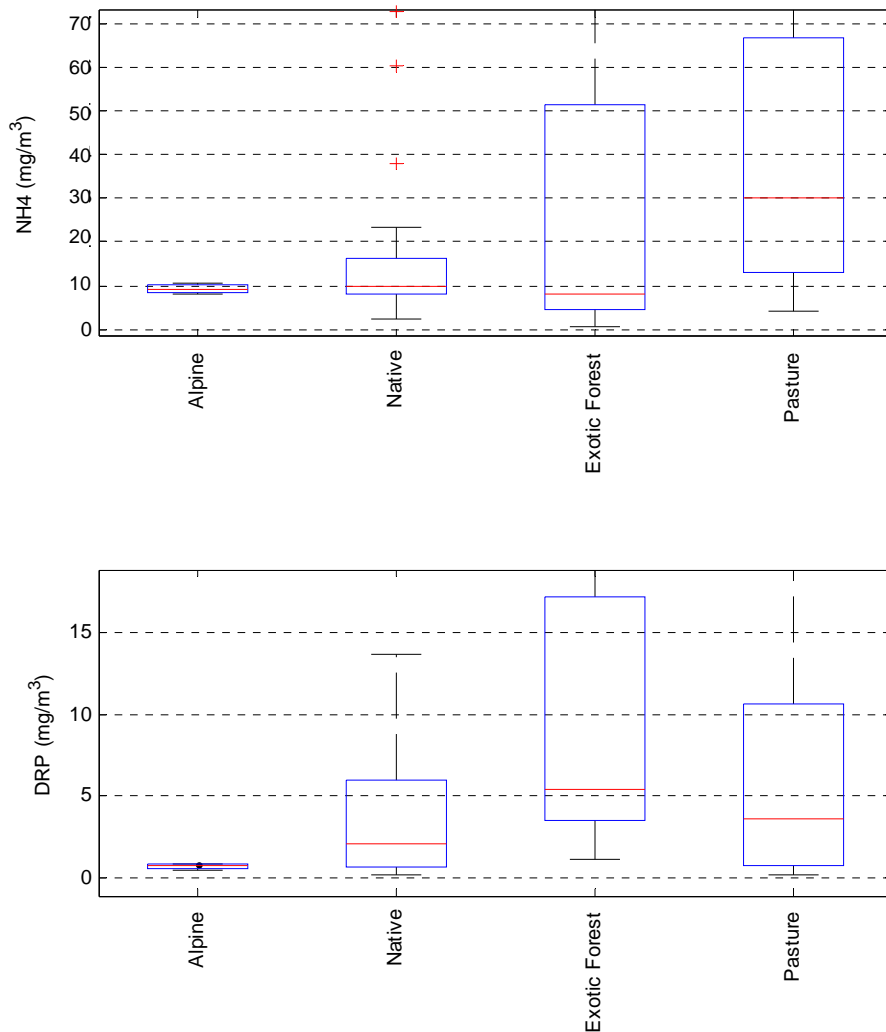


Note: Horizontal lines within boxes show median values, boxes show 25–75% data ranges, whiskers show 5–95% ranges, and pluses outliers outside the 5–95% ranges.

Pasture lakes with high water quality (TLI < 3) were exclusively Canterbury high-country lakes, where there is little fertiliser application and low stock density. Supertrophic and hypertrophic pasture lakes almost without exception were those with very high pasture (>50%) and low native (< 20%) cover.

The inorganic nutrient ($\text{NH}_4\text{-N}$, $\text{NO}_3\text{-N}$ and DRP) concentrations were excluded from the TLI methodology primarily because of the large number of very low values found for these parameters in monitoring programmes, and because they can be highly variable. This pattern was confirmed in the current data set across all land-use categories, although occasional high concentrations of inorganic nutrients were observed in both the exotic forest and pasture categories. Median values of $\text{NH}_4\text{-N}$ were $\leq 30 \text{ mg/m}^3$ for all classes, but values as high as 1 g/m^3 occurred in a few pasture lakes (see Figure 7). $\text{NO}_3\text{-N}$ (data not shown) was very low throughout ($< 20 \text{ mg/m}^3$ in all but a very small number of lakes). Median DRP values were low for all lakes (see Figure 7). They were similar for both native and pasture, very low (usually below detection limits) in alpine lakes, and most elevated in the exotic forest lakes. Both DRP and TP were highest in the exotic forest lakes, suggesting that either many exotic forests occur on soil with naturally high phosphorus yields, or that forestry practices are elevating P inputs to these lakes.

Figure 7: Box-and-whisker plots comparing NH₄-N and DRP across the four predominant land-cover classes (alpine, native, exotic forest and pasture)

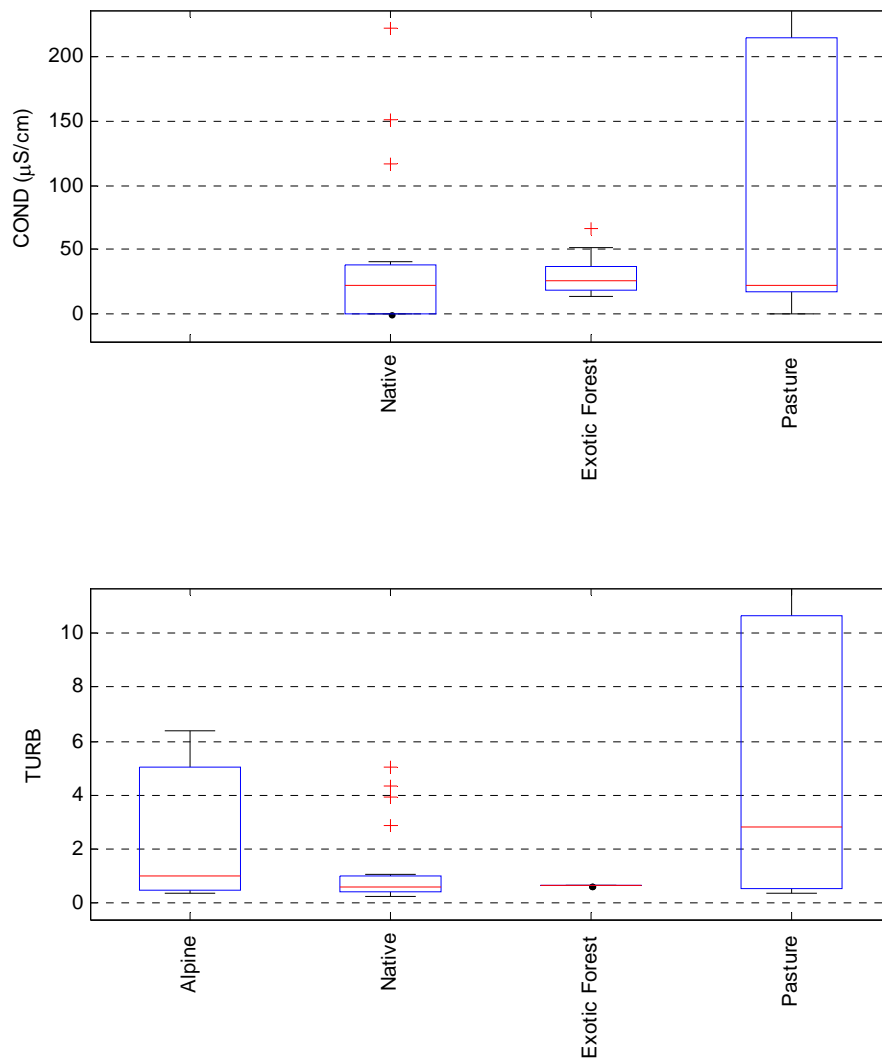


Notes: Horizontal lines within boxes show median values, boxes show 25–75% data ranges, whiskers show 5–95% ranges, and pluses outliers outside the 5–95% ranges.

Annual averages of concentrations of inorganic nutrients were frequently below detection limits for the lakes in both native and exotic forests, but were usually well above detection limits in the pasture class. Inorganic nutrients represent the bioavailable fractions of N and P, so this suggests that nutrient concentrations in pasture lakes are frequently in excess of those required for algal productivity, although this varies seasonally.

Conductivity and turbidity also differed among land-use classes (see Figure 8). For conductivity, median values were similar across classes but there was a strong trend for high conductivity values in the pasture class (high conductivity values are usually associated with higher trophic status). The highest turbidity values were also in the pasture class, which is consistent with known impacts of catchment development on lake turbidity. Relatively high turbidity values in many alpine lakes are associated with glacial flour.

Figure 8: Box-and-whisker plots comparing conductivity (COND, in $\mu\text{S}/\text{cm}$) and turbidity (TURB, in NTU) across the four predominant land-cover classes (alpine, exotic, native, and pasture)



Notes: Horizontal lines within boxes show median values, boxes show 25–75% data ranges, whiskers show 5–95% ranges, and pluses outliers outside the 5–95% ranges. No conductivity data were available for the alpine lakes.

The median values from the box plots in Figures 5 to 8 are summarised in Table 5, showing the increase in concentrations of water quality parameters, and the decrease in clarity (Z_{SD}) from alpine to native to exotic forest to pasture classes. Maps of water quality parameters are given in Appendix 3.

Table 5: Median values for water quality parameters in the four main land-cover classes (number of lakes in each class shown in brackets)

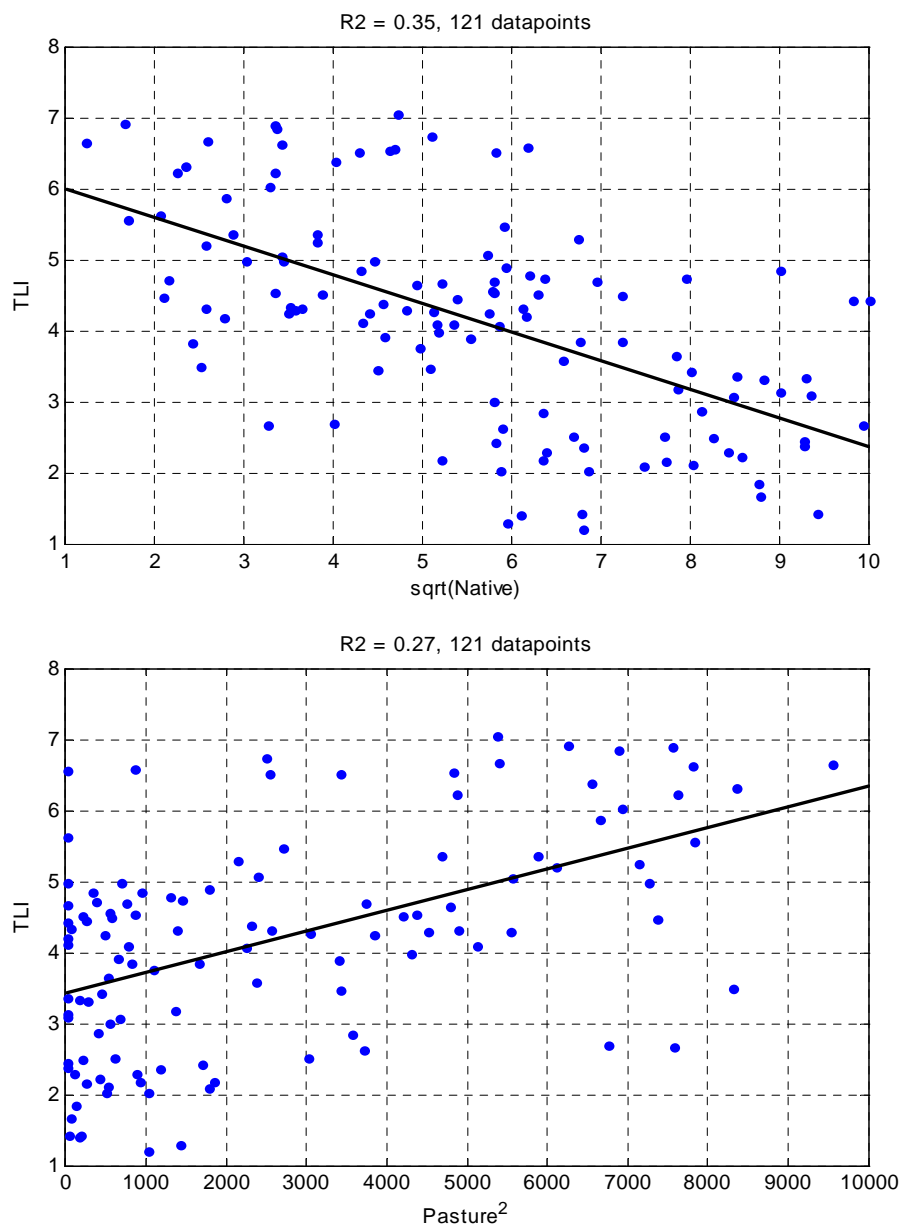
Parameter	Alpine (3)	Native (39)	Exotic (22)	Pasture (55)
TN (mg/m ³)	52	174	532	733
TP (mg/m ³)	3.1	8.3	47.3	51
Chla (mg/m ³)	0.93	1.7	4.2	9.4
Z _{SD} (m)	na	6.2	2.7	1.2
NH ₄ -N (mg/m ³)	9.0	10.0	8.0	30.1
DRP (mg/m ³)	0.8	1.7	5.4	4.0
Conductivity (µS/cm)	na	22	27	22.4
Turbidity (NTU)	1.0	0.6	0.65	2.8
TLI	2.0	3.1	4.4	4.9

Notes: Total number of lakes for each parameter ranged from 68 to 121 due to differences in monitoring programmes; na = no data available.

Figures 9 to 11 show significant regressions between water quality parameters and climate, land cover and lake morphology characteristics. Because many of the relationships are non-linear, Figures 9 to 11 are plotted using best-fit functions (linear, logarithmic, etc) for each relationship, as stated in the figure notes. Regressions were judged significant if they satisfied both $p < 0.05$ and $r^2 > 0.20$; this applies to all regressions shown in Figures 9 to 11.

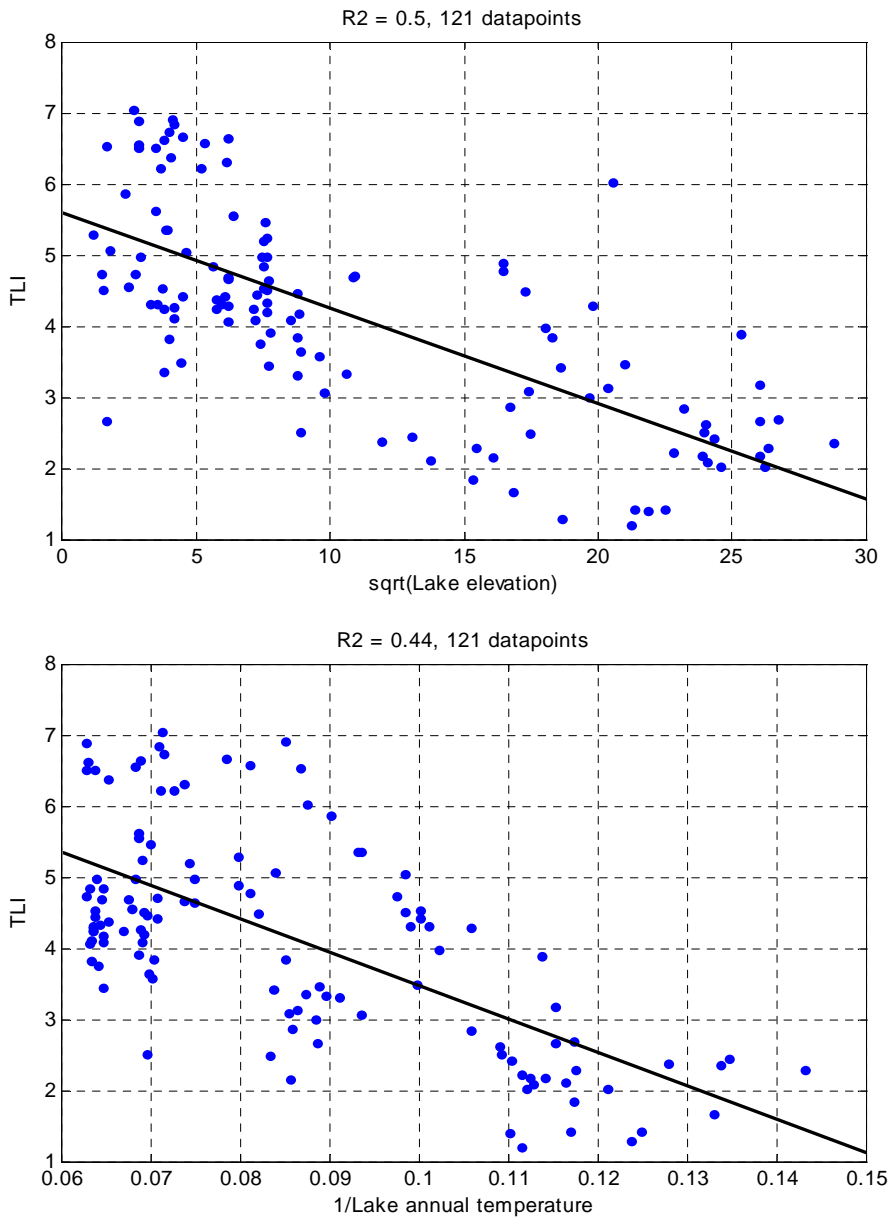
Given the patterns seen in the cover classes it was not surprising that TLI was also significantly related to the degree of the catchment retaining native cover and the amount of pasture in the catchment (Figure 9). The effects of native and pasture land cover on water quality parameters are summarised in Table 6. Low native cover and high pasture cover correlated particularly strongly with increased TLI and the four TLI parameters, and less strongly with increased NH₄-N and turbidity. Only NO₃-N, DRP and conductivity were not correlated with land use. Native cover was more strongly correlated with TLI parameters than pasture cover, consistent with the identification of lower water quality associated with other land uses such as exotic forest and urban cover.

Figure 9: Relationship between Trophic Level Index (TLI) and proportion of catchment in native cover (upper graph) and pasture (lower graph)



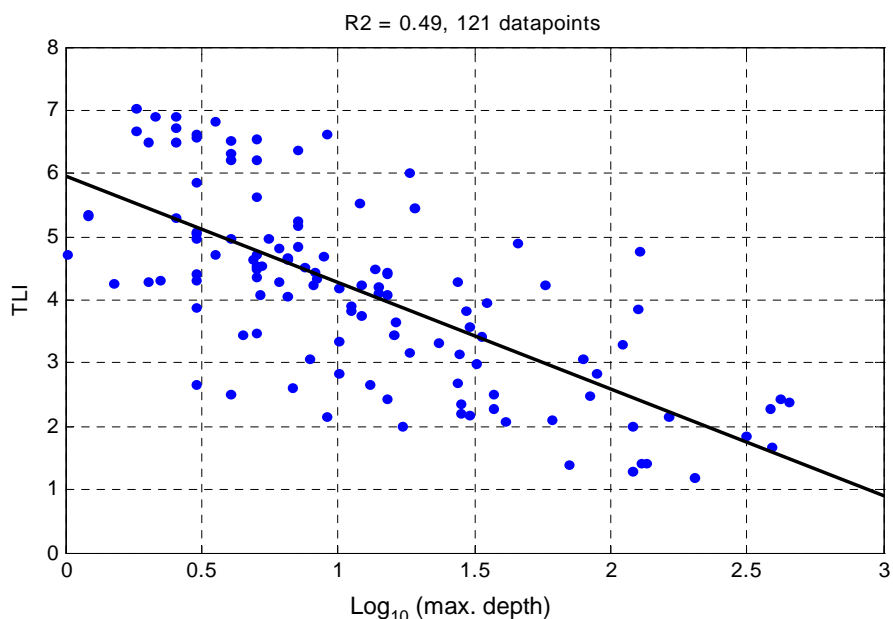
Note: Best fits were to square root (native cover) and square (pasture cover) transformations.

Figure 10: Relationship of Trophic Level Index (TLI) to altitude (upper graph) and inverse of mean annual temperature (lower graph)



Note: Best fits were to square root of lake elevation and linear to 1/temperature.

Figure 11: Relationship between Trophic Level Index (TLI) and maximum depth



Note: Best fit was to log₁₀ (maximum depth).

The scatter of points in Figure 9 is not surprising given that dominant cover is a coarse measure of land use. Lakes with similar pasture cover have widely different stocking rates and fertiliser use. Very few lakes with over 40% native cover had eutrophic (TLI > 4.0) values, and all of these had significant proportions of pasture or exotic forest in their catchments.

Only 10 lakes had more than 5% urban development, and TLI was over 4 for all these lakes. The two predominantly urban lakes both had eutrophic TLI values (4.3 for Pupuke and 4.6 for Hamilton Lake), but these lakes were less eutrophic than the other eight lakes with over 5% urban cover, all of which had high pasture cover (35–70%) contributing to their water quality. Hence, pasture may have a stronger effect on trophic level than urban cover, provided the urban development lacks point source discharges and has reticulated sewer systems, as is the case with Lake Pupuke and Hamilton Lake. Urban development may have a much greater effect if its waste treatment is by septic tanks or has other features such as stormwater discharges that allow nutrient run-off to lakes (eg, Gibbs, 1991).

It should be noted that, given the context of a broad national comparison of lakes varying widely in climate, area and depth, the correlations in Figure 9 and Table 6 are highly significant. Together with the following regressions in Figures 10 to 11, they explain most of the total variation in lake water quality, and the interactions between these environmental drivers is examined further by the multiple regression that follows.

Table 6: Spearman rank correlations for water quality parameters (three-year averages from 2004–2006) vs pasture land cover and native land cover

Parameter	% pasture	% native
TLI	0.44**	-0.60***
Chla	0.44**	-0.51**
TN	0.46**	-0.63***
TP	0.35*	-0.61***
1/Secchi depth	0.51**	-0.51***
NH ₄ -N	0.39*	-0.31*
NO ₃ -N	0.15	-0.13
DRP	0.12	0.03
Turbidity	0.38*	-0.49*
Conductivity	0.03	-0.08

Note: Significant correlations are shown for *p < 0.05, **p < 0.01, ***p < 0.001. Correlations are negative for native cover and positive for pasture.

Lake altitude and temperature were the other parameters that showed significant correlations with TLI (see Figure 10). High-altitude lakes are largely microtrophic and oligotrophic (TLI < 3), and most of the eutrophic, supertrophic and hypertrophic lakes are lowland lakes.

TLI increases strongly with temperature (Figure 10). Some of this relationship is due to the generally greater degree of catchment development in lakes in warm regions than in cold regions. However, Figure 10 shows that there are also numerous mesotrophic and eutrophic cold lakes, such as Lakes Emma, Clearwater and Johnson, all of which have high proportions of pasture in their catchments. The cold eutrophic lakes in Figure 10 are also almost all small, shallow lakes.

Figure 11 shows that deep lakes generally have higher water quality than shallow lakes. Note that there is considerable variation in water quality in the shallow lakes in the data set, largely due to the differences in land-use patterns already discussed. No significant regressions were found with the other physical descriptors lake area, fetch (lake distance over which prevailing wind blows), and residence time.

Summary for cover classes and regressions

- Concentrations of all water quality parameters increased across cover classes, from alpine, to native, to exotic forest, to pasture. Extreme high values were particularly common in the pasture class. Water clarity decreased from native, to exotic forest, to pasture classes.
- The TLI values reflected these differences. Alpine lakes were microtrophic and oligotrophic. Most native-dominated lakes were either oligotrophic or mesotrophic. Exotic forest lakes were mesotrophic and eutrophic. Most pasture lakes were eutrophic or supereutrophic, and almost all of the hypertrophic lakes were pasture lakes.
- There are highly significant correlations between TLI and the proportion of native and pasture cover in the catchment. TLI is lower (ie, with higher water quality) as native cover increases, and higher (ie, with poorer water quality) as pasture cover increases. TLI was not significantly correlated to any other land-cover type.
- All TLI water quality parameters showed a similar relationship to the native and pasture cover.
- TLI also correlated strongly with altitude (higher lakes are cleaner), lake depth (deeper lakes are cleaner), and climate (colder lakes are cleaner).

3.3 Multiple regression and classification

In this section we relate differences in lake water quality to all the possible drivers (eg, climate, land use, lake morphology) to identify the importance of different drivers and how they interact to control water quality. The regression tree analysis in section 3.3.1 uses the water quality data from the 121 lakes as dependent variables to generate groups of lakes with similar water quality, explaining them in terms of the possible drivers of water quality. In section 3.3.2 we look at how water quality differs among classes of lakes in the two existing classification schemes (Irwin, 1975 and Snelder, 2006). Note that in this exercise the classes are specified in advance on the basis of geological formation and environmental parameters, whereas in section 3.3.1 the groups of lakes are generated by the water quality data itself.

3.3.1 Regression tree analysis

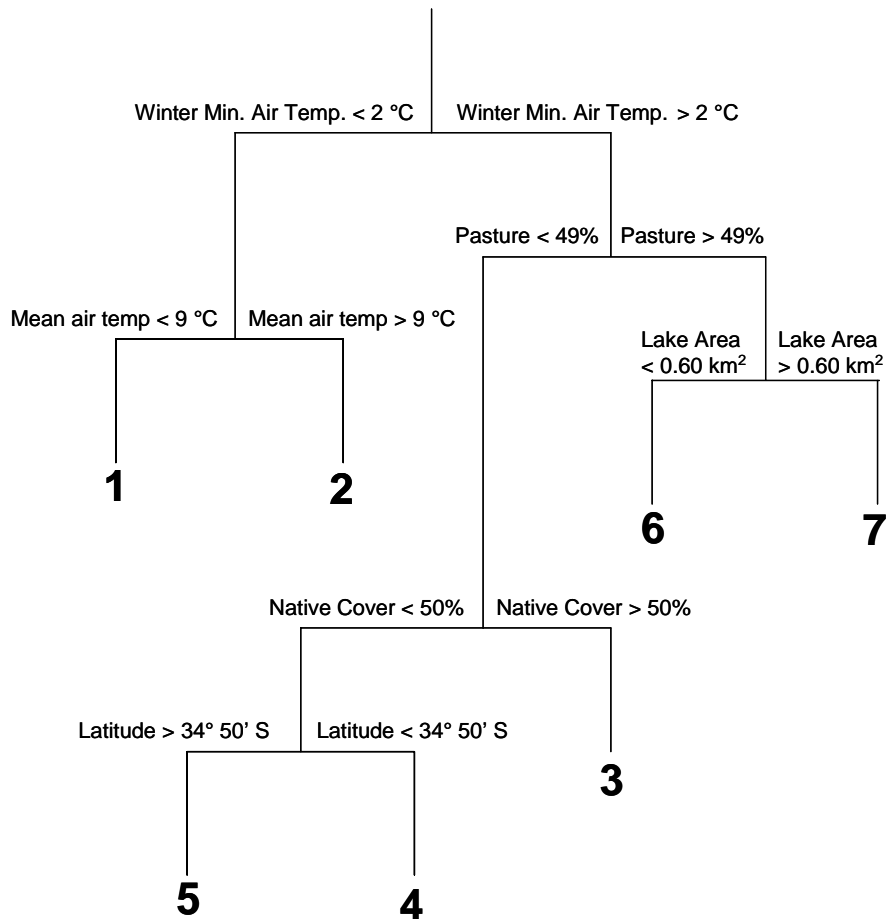
We used regression tree analysis to relate TN, TP and chl a to climate, lake morphology and land cover variables. Z_{SD} was excluded from the regression tree analysis because of the large number of lakes without Z_{SD} data.

Tree analysis chose a seven-leaf tree (ie, one in which the lakes were split into seven groups on the basis of regression) to best explain the water quality variation (Figure 12). The seven groups are groups of lakes that differ significantly in TN, TP and chl a concentrations. Variables related to climate, land cover and lake area were those that best explained the variation in TN, TP and chl a throughout the tree. Table 7 summarises the number of lakes in each group, the environmental conditions identified by the tree, how the groups differ in water quality, and gives examples for each group. The groups are highly consistent with the patterns observed in the land class and simple regression analyses presented earlier. The highest water quality is in very cold (ie, alpine and far southern) lakes with low pasture, and the poorest water quality is in

warm lakes with high pasture. Climate was the most important factor in lake water quality, with lakes in cold climates being identified as significantly lower in trophic level than warmer regions.

Land cover was the next most important factor, with group 3 including lakes in warmer climates with high native cover, and the lowest water quality occurring in groups 6 and 7 (> 50% pasture). The very lowest water quality in group 7 includes the large, shallow lakes at low altitudes with high pasture cover, whereas group 6 includes the smaller pasture lakes. Groups 4 and 5 include those lakes in which both native and pasture land are individually less than about 50% cover. For many of these lakes, exotic forest is the dominant land use. In other cases, pasture or native cover may still be the greatest single land-use category (eg, Lake Waipori, in Otago, with cover of 40% native, 38% pasture and 21% exotic forest).

Figure 12: Regression tree explaining variation in TN, TP and chl_a in terms of environmental and spatial variables (climate, lake morphology, land cover, etc)



Notes: The analysis produced seven groups of lakes, numbered in order of decreasing water quality (see Table 7 for further explanation). Temperatures are climate variables (winter air temperatures and mean annual temperatures). The latitude split (group 4) includes a small number of far north lakes on the Aupori Peninsula.

The latitude branch splits off a subset of the Aupori Peninsula lakes north of Houhora (group 4), in which *chl_a* is much lower than would be expected from their TN and TP data. Although the tree has picked latitude for this split, most of the other Aupori lakes are in groups 5 and 6 and it is unlikely that any climatic factor is responsible. The reason for the distinct water quality pattern in these lakes is not clear: their Z_{SD} ranges from 1.5 m to 6 m, which should allow considerable algal productivity, and no other likely features are evident. These are a cluster of the northernmost lakes in New Zealand, and there may be aspects of local geology leading to high dissolved organic N and P concentrations that are not available to algal productivity.

Table 7: Characteristics and examples of the regression tree groups of lakes with TN, TP and *chl_a* as the variables

Group	<i>n</i>	Environment description	Water quality	Examples
1	26	Very cold climates	Excellent (all microtrophic or oligotrophic)	Wanaka, Sumner, Te Anau, Tekapo
2	21	Cold winters but milder mean annual temperatures	Good (mostly oligotrophic and mesotrophic)	Rotoma, Tikitapu, Brunner, Lady
3	10	Mild climates, > c. 50% native catchment cover	Good (some oligotrophic, most mesotrophic)	Kai-iwi, Mahinapua, Ototoa
4	7	Mild climate, native and pasture cover are both < c. 50%, far northern	All very high TP, mostly high TN, but very low <i>chl_a</i>	A small subset of far north (Aupori Peninsula) lakes
5	25	Mild climate, native and pasture cover are both < c. 50%	Poor (mostly eutrophic and some supereutrophic)	Rotorua (Bay of Plenty), Waiparera, Tomarata, Rotokawau
6	20	Mild climate, > 50% pasture cover, lake area < 0.60 km ²	Very poor (mostly supereutrophic)	Tomahawk Lagoon, Serpentine, many Northland lakes
7	12	Mild climate, > 50% pasture cover, lake area > 0.60 km ²	Extremely poor (all hypertrophic)	Horowhenua, Ellesmere, Whangape

Notes: *n* = number of lakes in each group. Total number = 121.

One initially surprising feature of the tree was that depth was not selected for any of the splits. This is because depth is strongly correlated with other parameters that were chosen in the regression (climate, area and land cover). Most of the large, deep lakes are in cold areas, with high proportions of their catchments in native cover. Of the 121 lakes, only 20 had maximum depths over 50 m, none of which had more than 40% pasture or exotic forest cover. Only one of these lakes, the urban Lake Pupuke, had low native cover.

We also experimented with trees for lakes for which we had data for all four main parameters (TN, TP, *chl_a*, and Z_{SD}), which reduced the number of lakes in the regression to 75 and produced a tree with six groups instead of seven (Table 8). It should be noted that the 75 lakes for which we did not have Z_{SD} included most of the best-quality microtrophic and oligotrophic lakes. Because this tree does not represent the full range of water quality in the 121 lakes, the tree output in Figure 12 and Table 7 is probably more suitable for management purposes, and we have not analysed the output in Table 8 in as much detail. However, it has used similar factors in generating its groups (ie, land cover and climate, but also altitude). Altitude was probably not chosen by the larger tree for the same reason as depth; ie, it is strongly correlated with climate and native cover. The single regressions above also emphasised that land cover, climate and altitude are all important factors for water quality.

Table 8: Characteristics and examples of the regression tree groups of lakes using all four TLI parameters as variables

Group	<i>n</i>	Environment description	Water quality
1	11	Pasture < 50%, cold climate	Mostly oligotrophic
2	8	Far northern Aupori Peninsula subset (see above)	All very high TP, moderate TN and Z _{SD} , but very low chl _a
3	23	Pasture < 50%, mild climate, altitude > c. 15 m asl	Mesotrophic and eutrophic
4	6	Pasture < 50%, mild climate, altitude > c. 15 m asl	Eutrophic and supereutrophic with generally high TP
5	12	Pasture > 50%, > 40 m asl altitude	Eutrophic and supereutrophic with high chl _a values
6	15	Pasture > 50%, < 40 m asl	Almost all hypereutrophic

Notes: *n* = number of lakes in each group. Total number = 75 m asl = metres above sea level.

The classifications emphasise that large, shallow lakes are highly likely to be supereutrophic or hypereutrophic, that lowland lakes have worse water quality than upland lakes, and that higher native cover is associated with higher water quality.

Summary for regression trees

- The regression tree analysis produced seven groups of lakes differing in water quality. The highest water quality occurred in groups of lakes with cold winters or high native cover. The worst water quality was in lakes with over about 50% pasture cover, especially large, shallow lakes.
- Water quality groups were mainly defined by climate (temperature), native and pasture cover, altitude and lake area. Large shallow lakes, lower altitude, warmer climate, and higher pasture cover selected groups of lakes with poorer water quality.

3.3.2 Relationship to lake classification

Ministry for the Environment (2006) compared the TLI data from councils across the Irwin (1975) categories and found that dune lakes and peat lakes were most likely to be in eutrophic or higher classes, whereas glacial lakes were most likely to be oligotrophic or microtrophic. As he noted, this is because dune and peat lakes are mostly small and shallow, whereas glacial lakes are usually larger and/or deeper. The mode of lake origin is not itself a direct cause of trophic state; rather, lake morphometry is the important variable within mode of origin that affects susceptibility of lakes to different land uses. Dune lakes include many oligotrophic lakes, because they often do not have surface inflows and so have very low nutrient inputs if their catchments are unmodified. Dune lakes also include some of the most eutrophic examples because they are shallow and poorly flushed, making them susceptible to increased nutrient load.

The Snelder (2006) classification recognises that climate, surface area and depth are important factors controlling lake ecosystems, because of their effect on mixing patterns and phytoplankton productivity. Table 9 compares water quality among the seven national-scale classes. Note that most of the lakes for which we had data were in the large, deep class (19 lakes); the medium, warm class (29); or the small, warm class (62).

Table 9: Median values of the component TLI indices for chl_a, Z_{SD}, TN and TP in the seven lake classes

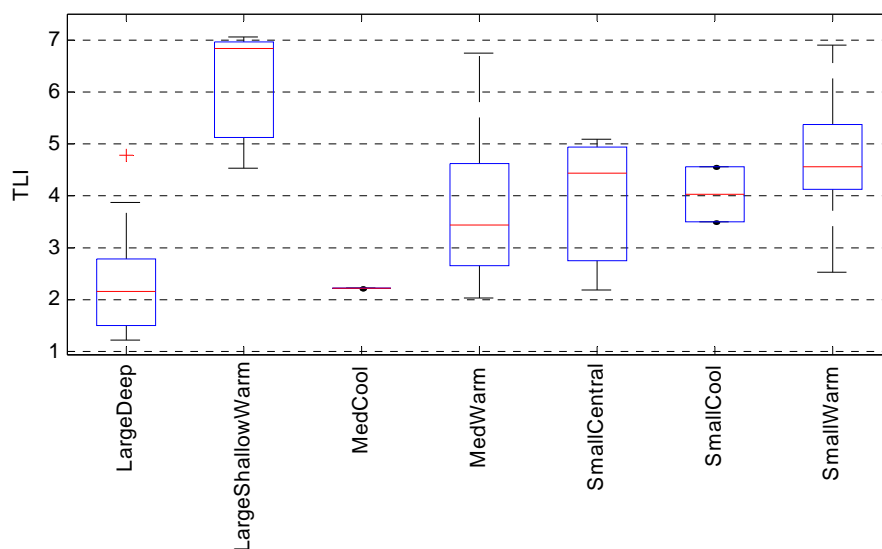
Class	N	TLc	TLs	TLn	TLp
Small warm	62	4.14	4.33	4.87	5.18
Small central	3	4.14	–	4.94	4.21
Small cool	2	–	–	–	–
Medium cool	1	–	–	–	–
Medium warm	29	3.53	3.53	3.88	3.26
Large shallow warm	5	7.06	6.24	6.43	6.75
Large deep	19	2.22	2.66	2.12	2.00

Notes: *n* = number of lakes in each class. Z_{SD} data were absent from all but four classes. No estimates were made for small cool and medium cool classes (< 3 lakes).

All four component TLI indices show significant differences between these classes. Table 9 confirms that the large, deep lakes in New Zealand generally have good water quality (median values generally oligotrophic), medium-sized lakes have intermediate water quality, and small lakes have poor water quality. The large, shallow lakes had very poor water quality. Despite the small number of lakes in some classes, there is also a clear tendency in Table 9 for higher water quality in cooler lakes of similar size, consistent with the patterns detected in the regression tree analyses. We found poor water quality in cool lakes with low native and high pasture cover in the regressions; this suggests that higher water quality in cold climates reflects the historically lower human pressures in their catchments rather than any strong resilience to degradation in colder climates. Small lakes in cold regions therefore appear to be equally at risk of degradation to those in warm regions, given similar pressures.

Figure 13 summarises the differences in water quality using TLI. Bearing in mind the limitations of numbers of lakes in the different classes, the pattern of deteriorating water quality on the gradients from deep to shallow, and cool to warm, is evident in this comparison.

Figure 13: Box-and-whisker plots showing differences in TLI for the seven environmental classes



Notes: Horizontal lines within boxes show median values, boxes show 25–75% data ranges, whiskers show 5–95% ranges, and pluses outliers outside the 5–95% ranges.

Summary for classification groups

- Comparison of water quality across the classification groups that are based on climate and lake size and shape independently supports the conclusions of the regression tree analysis: water quality is higher in deeper lakes than in shallow lakes, and higher in large lakes than in small lakes. Large, shallow lakes have especially poor water quality.

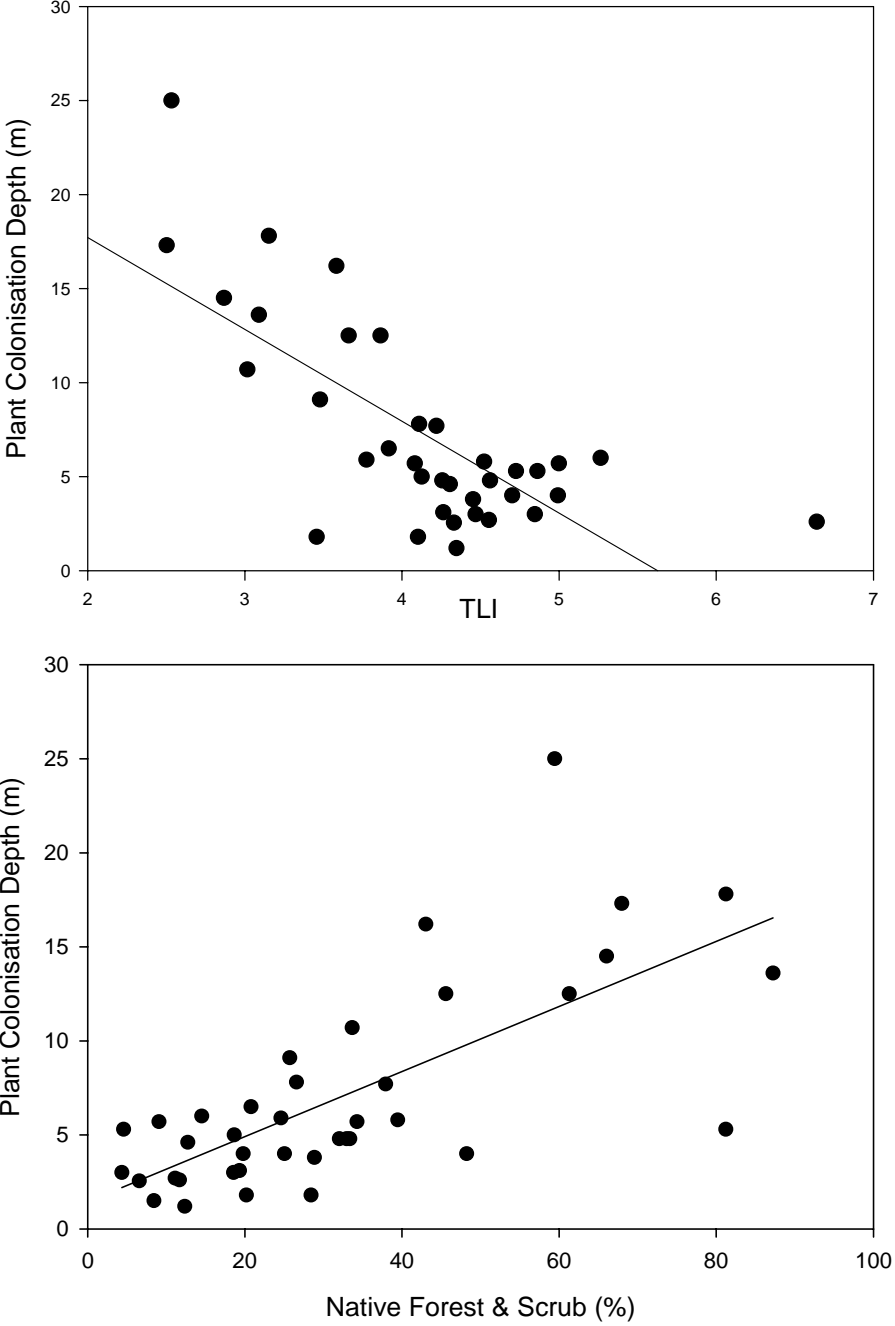
3.4 Relationships between water quality and LakeSPI data

There were 39 lakes for which both LakeSPI and water quality data were available, from three regions (Northland, Waikato and Bay of Plenty). Although the geographic coverage and range of catchment land uses is therefore limited, these lakes included a range of trophic states from oligotrophic to hypertrophic.

There was a highly significant relationship between TLI and the plant colonisation depth for these lakes (see Figure 14). Plant depths in lakes are well known to be strongly correlated with light attenuation in the water, which is captured in the TLI by Z_{SD} (Schwarz et al, 2000). High nutrient concentrations and their associated high algal biomass can be clearly linked to shallower depth limits in the macrophyte community. Plant depth was also significantly correlated with those factors shown earlier to be related to water quality, especially catchment land use. Figure 14 shows how low native cover in the catchment was strongly related to shallow depths in the plant community.

However, there were no significant relationships between any of the catchment and water quality variables with either the native or exotic condition indices in the lakes. The presence of introduced plant species in New Zealand lakes is changing with time and is largely a function of boat access and boating activity (Johnstone et al, 1985). Native diversity is often affected by pressures such as the impacts of exotic species and water-level management, as well as water quality. These may all be reasons why species composition was not related to land use or water quality in this data set.

Figure 14: Upper: Relationship of the maximum depth of submerged aquatic plant growth recorded in LakeSPI analysis to trophic level index (TLI), $r^2 = 0.52$. Lower: Relationship of the maximum depth of submerged aquatic plant growth recorded in LakeSPI analysis to proportion of catchment in native cover, $r^2 = 0.51$



Summary for LakeSPI comparison

- The depth of plant colonisation in lakes, which is one of three components of the LakeSPI score, was very strongly correlated to water quality and catchment land use. This is because water clarity is lower at higher trophic levels, reducing light penetration for plant growth.
- Native species diversity and the invasion of exotic species were not related to water quality. Other pressures, such as boating activity and water-level management, are important for species composition. Water quality is therefore just one of a number of aspects of ecological condition that are important to consider for lake condition assessment.

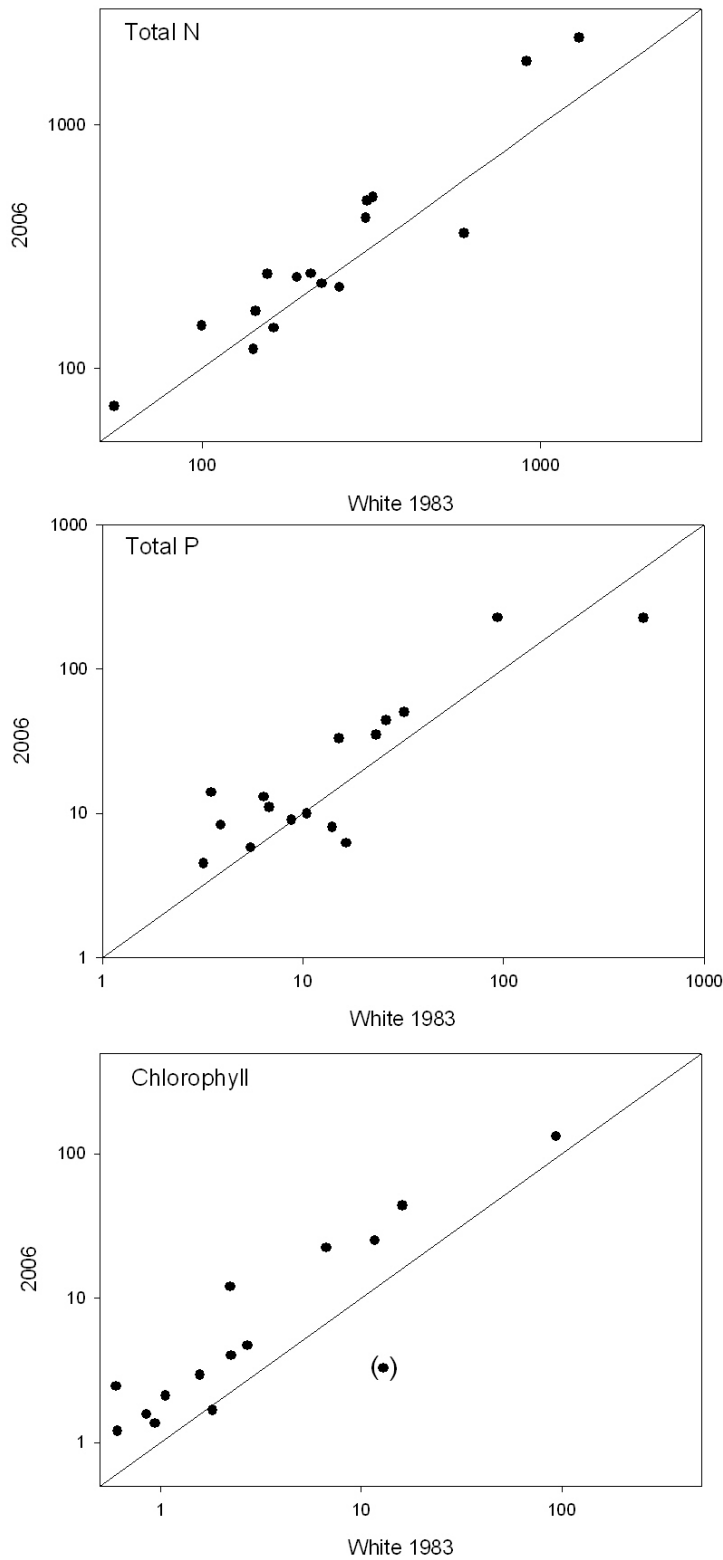
3.5 Trends in lake water quality

3.5.1 Long-term comparisons with data from 1983 and 1996

Comparisons with historical data need to be interpreted cautiously. The precision, accuracy and detection limits of analytical methods change over time, as do sampling sites and reporting methods. These caveats need to be kept in mind when looking at Figures 15 and 16 below, especially with the 1983 data, which were compiled from a range of studies carried out with different timeframes and data quality control. In general, the 1983 data are from occasional sampling, usually in summer, whereas the modern data are three-year averages of monthly or quarterly measurements. The 1996 data are more directly comparable with the 2006 data because similar sampling protocols were followed (Burns and Rutherford, 1998).

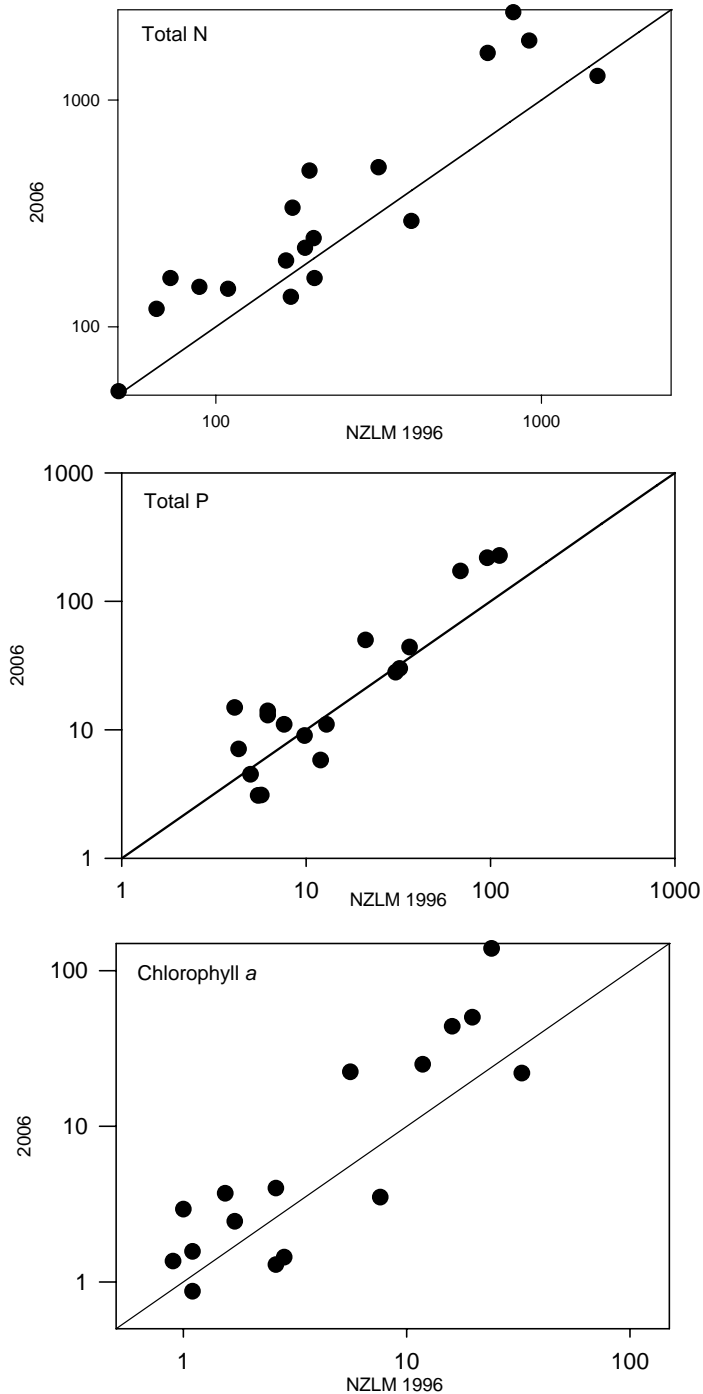
Nevertheless, a comparison of this type is helpful for developing a general picture of changes in lake water quality over the last 20 years, especially given the long-term nature of change in lake water quality and the relatively small number of lakes that have had regular, detailed monitoring over this time. Although Figures 15 and 16 do not lend themselves to detailed lake-by-lake comparisons or trend analysis, they provide a useful visual overview of how our lakes have changed since the 1980s.

Figure 15: Comparison of total N, total P and chlorophyll a concentrations (mg/m³) between data of White (1983) and current data for 16 lakes



Notes: The diagonals are 1:1 lines; points above the diagonals are increases in concentration and below the line are decreases in concentration from 1983 to 2006.

Figure 16: Comparison of total N, total P and chlorophyll a concentrations (mg/m^3) between 1996 data of the NZ Lake Monitoring programme and current data for 17 lakes



Notes: The diagonals are 1:1 lines; points above the diagonals are increases in concentration and below the line are decreases in concentration from 1996 to 2006.

Figures 15 and 16 strongly suggest differences in water quality between the three time periods, with large increases in TN, TP and chl a apparent in both comparisons. Note that the axes in Figures 15 and 16 are logarithmic, so many of the changes between the time points are relatively large.

There are 26 lakes in total across the two comparisons. Only eight of these have data for 1983, 1996 and 2006, all but one of which are Bay of Plenty lakes. Because of this regional bias, we have not made direct comparisons between 1983 and 1996 or involving all three time periods. Nevertheless, most of the lakes have undergone large deteriorations in water quality in both comparisons, and these lakes are broadly representative of the range of lakes that have combinations of pastoral catchments, warmer climates and lower altitudes.

3.5.2 Recent trends according to TLI methodology

The 49 lakes in the data set with sufficiently detailed records for trend analysis included lakes in Northland (3), Auckland (7), Waikato (14), Bay of Plenty (12), Manawatu (Lake Horowhenua), Wellington (Lake Wairarapa), Otago (10), and West Coast (Brunner). Table 10 identifies those lakes with significant trends in water quality. In general, it presents a picture of northern lakes decreasing in water quality and more stable water quality further south. Although there was some variability in trends among parameters in some lakes, probable and definitely declining quality were most common in shallow, lowland lakes (eg, Rotokauri, Waikare) or in lakes such as Rotoiti (Bay of Plenty) that have well-documented point source inputs.

No change was detected for most of the lakes in Table 10, although there are two important qualifications to this finding. First, many of these lakes have already become supertrophic and hypertrophic, so additional nutrient run-off is unlikely to increase *chl_a* and decrease Z_{SD} further because algal growth is already nutrient-saturated. Second, it needs to be reiterated that deterioration in lake water quality is a long-term process, and that it is often non-linear (ie, there may be no apparent change in water chemistry for several years after changes in land use, until critical thresholds are passed or the food web structure changes). Some of these lakes may therefore be undergoing deterioration but the current data sets are still too short to reveal this.

Regression tree analysis was conducted to relate Percent Annual Change to climate, lake morphology and land cover. Relatively few lakes showed large, consistent changes in all parameters, and no clear regression trees could be produced following the usual one standard error regression approach. Altitude was the one parameter that could robustly split the trend data, with the lakes less than 50 metres above sea level (masl) having high PAC increases (median PAC > 6% for TN, TP and *chl_a*), and lakes with more than 50 m asl generally having no significant PAC.

Table 10: Recent trends in lake water quality for the 49 lakes (listed from north to south) with sufficient data for trend analysis, calculated using the Burns et al (2000) TLI methodology

Lake	Years of data since 1990	Number of data points	Current TLI	PAC trend (p levels as in Burns et al, 2000)
Waikere	5–16	24–41	3.6	Possible deterioration
Taharoa	4–16	24–38	2.5	No change detected
Kai-iwi	4–16	24–40	3.6	No change detected
Spectacle	16	46–59	6.4	No change detected
Tomarata	16	51–59	4.4	No change detected
Otooa	16	46–59	3.8	No change detected
Kuwakatai	16	48–58	5.5	No change detected
Kereta	16	43–57	4.3	Possible improvement
Pupuke	16	44–58	4.3	No change detected
Wainamu	16	48–63	4.4	No change detected
Waikare	16	79–94	7.1	Probable deterioration
Whangape	4	23–44	6.8	Probable improvement
Hakanoa	16	37–57	6.7	No change detected
Waahi	16	275–379	6.2	No change detected
Rotokauri	10	73–125	6.3	Definite deterioration
Hamilton Lake	17	210–230	4.7	Definite improvement
Mangahia	4	24–25	6.6	No change detected
Maratoto	16	77–122	5.2	Possible deterioration
Rotomanuka	16	217–415	4.7	Probable deterioration
Mangakawhare	4	22–23	6.2	No change detected
Serpentine	4	95–185	5.0	No change detected
Ngaroto	12	121–244	6.4	No change detected
Okareka	15	117–220	3.4	No change detected
Okaro	14	81–159	6.0	Probable improvement
Okataina	15	73–114	3.1	Possible deterioration
Rerewhakaaitu	15	92–198	3.5	No change detected
Rotoehu	15	148–429	4.5	No change detected
Rotoiti	14–15	279–490	4.8	Definite deterioration
Rotokakahi	13	52–109	3.0	No change detected
Rotoma	15	77–127	2.5	No change detected
Rotomahana	12–15	57–117	3.9	Possible improvement
Rotorua	15	217–721	4.9	No change detected
Tarawera	15	85–135	2.9	No change detected
Tikitapu	15	84–137	3.2	Possible deterioration
Taupo	13	172–187	2.2	Possible deterioration
Horowhenua	5–8	69–131	6.7	No change detected
Wairarapa	12	32	5.3	No change detected
Brunner	10	75	3.3	Probable deterioration
Hawea	6–11	33–62	1.7	No change detected
Wanaka	6–11	33–63	1.9	No change detected
Hayes	7–10	30–43	4.0	Probable improvement
Dunstan	6–9	35–50	2.1	No change detected
Johnson	7–8	35–44	4.3	No change detected
Wakatipu	6–11	34–66	2.3	No change detected
Te Anau	3–6	48–177	2.5	No change detected
Manapouri	4	63–147	2.4	No change detected
Waipori	8–11	39–64	4.7	No change detected
Waihola	8–10	39–59	4.3	No change detected
Tuakitoto	6–11	25–63	5.1	No change detected

None of the 49 lakes in Table 10 were in alpine catchments, only one (Rotokakahi) was in a predominantly exotic forest catchment, and two (Pupuke and Hamilton Lake) were in urban catchments. Table 11 compares these trends for the remaining lakes in pasture and native forest catchments. Although the number with no change detected is similar in both categories, most of the pasture lakes with no change are already eutrophic, supertrophic or hypertrophic. A map of water quality trends is given in Appendix 4.

Table 11: Comparison of numbers of lakes in Table 10 in native catchments and pasture catchments in relation to water quality trends

Change	Native (<i>n</i> = 19)	Pasture (<i>n</i> = 27)
Definite deterioration	1 (Rotoiti, Bay of Plenty)	1 (Rotokauri)
Probable deterioration	1 (Brunner)	2 (Rotomanuka, Waikare)
Possible deterioration	3 (Taupo, Okataina, Tikitapu)	2 (Waikere, Maratoto)
No change detected	13	18
Possible improvement	1 (Rotomahana)	1 (Kereta)
Probable improvement	0	3 (Whangape, Okaro, Hayes)
Definite improvement	0	0

Note: Names of lakes showing change are identified. Lake Rotokakahi (exotic forest catchment) was excluded.

The one native catchment lake with definite deterioration is Rotoiti (Bay of Plenty); the reasons for this were discussed earlier. Lakes Taupo and Brunner are two large lakes with predominantly native catchments within which conversion to pasture and increased nutrient runoff have recently been linked to decreased water quality (Gibbs, 2006; Kelly, 2006). In the case of Lake Taupo, other indicators such as hypolimnetic nitrate accumulation and changes in littoral ecology are providing further evidence of the early stages of deterioration. There are examples of both deterioration and improvement in the pasture lakes in Tables 10 and 11. The deteriorating lakes are all shallow Waikato lakes with a well-documented history of agricultural nutrient loading. However, an encouraging feature of Table 11 is the three pasture lakes showing probable improvement. Lakes Okaro and Hayes have catchment management plans in place involving actions such as restoration of marginal wetlands and riparian retirement of grazing activity, which may have contributed to their improvement. In Hamilton Lake and Lakes Whangape and Kereta, recovery of submerged aquatic vegetation has been linked to recent improvements in water quality.

Summary for trends

- Comparisons of current and historical data strongly suggest that many lakes have deteriorated in water quality in New Zealand over the last 20 years.
- For recent trends, the shallow, lowland lakes in the North Island were most likely to show probable or definite deterioration.
- Most of the pasture lakes for which there was adequate data for recent trend analysis are already supertrophic or hypertrophic. Some of these are continuing to deteriorate.
- Some lakes where catchment restoration has been undertaken show improved water quality.

3.6 Nationwide extrapolation of state and pressure

We applied the regression tree of Figure 12 to all lakes in the nationwide database to develop a picture of likely water quality in New Zealand’s full lake inventory (Table 12). Approximately 60% of New Zealand lakes occur in regions with very cold winters and have high native and low pasture cover, and probably retain excellent water quality. However, approximately 30% are likely to have water quality that is poor or very poor. Large, lowland lakes almost all have extremely poor water quality.

Table 12: Distribution of 3,820 lakes in New Zealand larger than 1 ha in each of the water quality groups*

Group	Water quality description	Number of lakes	% of lakes
1	Microtrophic or oligotrophic lakes in very cold climates; largely unmodified catchments	1,638	43.0
2	Oligotrophic and mesotrophic lakes with cold winters	674	17.6
3	Good water quality in mild climates and high native cover	275	7.2
4	Aupori Peninsula subset	15	0.4
5	Larger eutrophic lakes with mixed land use in catchments	278	7.3
6	Small, shallow, pastoral lakes; mild climate; mostly supertrophic	906	23.6
7	Large hypertrophic lowland and coastal lakes	34	1.0
Total		3,820	100

* As defined by the regression tree groups (Figure 12; Table 6).

The Snelder (2006) classification can be used to identify the likely future trends in lake water quality, based on the strong relationships between catchment land cover, size and climate found in the water quality data (Table 13). Note the large proportion of small, warm and small, medium-temperature lakes (73%) that have non-natural catchment classes (exotic, pasture or urban), and the large proportion of lakes in total with non-natural catchment classes (1,871 lakes, or 50% of the total), and that there is a much higher proportion of medium and large lakes than small lakes with native catchments. Table 13 suggests that the water quality of small lakes is likely to be under high pressure, that lowland and northern lakes are likely to be under high pressure, and that many New Zealand lakes have predominant catchment land cover leading to degraded water quality.

Table 13: Number of lakes in each of the seven primary classes of the Snelder (2006) classification with alpine, exotic forest, native and urban catchment classes

Class	Alpine	Exotic forest	Native	Pasture	Urban	Total
Small warm		178	251	1,086	39	1,554
Small central	14	42	396	468	3	923
Small cool	290	2	773	9		1,074
Medium cool	12		63			75
Medium warm		5	58	31		94
Large shallow				4		4
Large deep	2		26	4		32
Total	318	227	1,567	1,602	42	3,756

Note: Some of the 3,820 lakes for which catchments cannot be clearly defined (mainly small warm lakes) are excluded.

Summary for nationwide extrapolation

- Overall we estimate that 60% of all New Zealand lakes are likely to have good or excellent water quality. Most of these are in cold climates, especially at high altitudes and other remote areas.
- We estimate that approximately 30% of New Zealand lakes are likely to have water quality that is very poor or extremely poor. The majority of lowland lakes are likely to have very poor or extremely poor water quality.
- Approximately 50% of lakes are not in native or alpine-dominated catchments, most of which are not in cold climates, indicating extensive pressure on lake water quality.

4 Conclusions

During the period of rapid development of understanding of the limnology of New Zealand lakes (1970–1990), many empirical relationships were revealed showing increases in lake productivity and eutrophication of lakes due to increases in nutrient enrichment. Much of the early research focused on point source discharges (eg, Lakes Rotorua and Rotoiti, Bay of Plenty), and the feasibility and time frames required for restoration after diversions of these. More recent concerns have focused on diffuse nutrient run-off due to catchment development and changes in land use. In particular, recently developed models of nutrient run-off strongly suggest that lake water quality will be lower in developed catchments than in undeveloped catchments. The analysis in this study has shown that all key water quality parameters and TLI indices were poorer in pasture catchments than in either native or exotic forest catchments. Most of these degraded rural lakes were lowland lakes.

The patterns in water quality seen with land use are consistent with our understanding of factors responsible for lake degradation. Catchment development is known to increase nutrient loads to lakes in tributaries and ground water, and to lead to increased phytoplankton productivity, decreased water clarity and changes in dominant algal species. Large, deep lakes take a long time to respond to increased nutrient loads associated with catchment development as a result of their long residence times, and hence show greater initial resilience to nutrient inputs than shallow lakes. However, large lakes do suffer extensive degradation if nutrient enrichment continues, and are more difficult to restore than shallow lakes because of longer residence times. There is evidence of degradation occurring in some of our larger lakes where catchments have been developed (Vant and Huser, 2000), although that is not apparent in the data analysed in this report. Degradation is likely to occur in other large lakes if nutrient inputs increase (eg, as a result of conversion from native cover to pasture).

Lack of knowledge of the range of lake water quality in pre-European times is often raised as an issue when assessing deterioration caused by human activity. The extent to which some lakes may have had naturally eutrophic conditions is an important consideration in lake water quality studies. The best evidence on the pre-European or pristine state comes from palaeolimnological studies of lake sediments. Existing palaeolimnological evidence in New Zealand suggests that some shallower lakes may have had moderately high nutrient concentrations, but this is probably less widespread than often claimed. Early botanical records from shallow lakes in the Waikato, for example, indicate very high water clarity in pre-European times. In our opinion, the eutrophic, supereutrophic and hypereutrophic conditions in the current state are largely the result of human activity.

The regression tree analysis suggests that climate change is likely to be an important issue exacerbating deterioration in lake water quality in future. Temperature featured as an important factor throughout the regression trees, and this strongly suggests that if lakes become warmer, their sensitivity to land use in the catchment will also increase.

The limited number of small lakes in monitoring programmes compared to the number of small lakes in New Zealand, and the greater degradation of small lakes than large lakes, suggests that they are likely to be under-represented in the national picture of lake water quality in New Zealand. There has also been much less research carried out on nutrient cycling and food web structure in small lakes than in shallow lakes, so there is less understanding of how they respond to nutrient inputs. Future research issues for these lakes include the nature of internal nutrient regeneration, the importance of polymixis and short-term stratification patterns, and the effects of nutrient enrichment on their food-web structure.

As part of this project, we also collected dissolved oxygen data from councils. However, oxygen profile data were restricted to a small number of regions and lake types and there were not enough records for broad-scale geographic, land-use and lake-type comparisons. It should be stressed that dissolved oxygen is a key indicator of degradation in lakes, and more extensive data sets would be valuable for understanding lake status and trends. Profile data will continue to be important for deeper monomictic lakes, but shallow polymictic lakes are likely to show diurnal oxygen cycles with nocturnal de-oxygenation accompanying eutrophication. The recent development of oxygen sensors with data-logging capacity makes nocturnal monitoring and monitoring over longer time periods more feasible.

Overall, it can be seen that New Zealand still retains a large number of relatively oligotrophic lakes, although most of these are in high-altitude areas with low human pressures. Eutrophication processes have nevertheless evidently resulted in extensive increases in nutrient status and biological productivity on a wide scale, and the worst water quality is strongly associated with pasture in the catchment. Although much of the early water quality science in lakes focused on the effects of point source discharges, diffuse catchment run-off is clearly implicated as a major cause of the current condition of lakes throughout the country. Application of nutrient run-off models in conjunction with improved understanding of in-lake processes in lakes of different sizes will be critical to understanding, managing and reversing these processes. Restoration will need to focus on minimising loads throughout catchments, and understanding the time scales required for water quality to recover in relation to residence times and internal nutrient regeneration. The examples of improved water quality in lakes with restoration plans in place show that restoration is feasible, although it is usually a prolonged and expensive exercise.

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Appendix 1: Glossary of common limnological terminology used in this report

<i>Epilimnion</i>	The surface water mass in a lake above the thermocline (see stratification), which is well mixed and therefore of uniform temperature; the surface mixed layer.
<i>Eutrophic</i>	High in nutrient concentration (hence eutrophication – nutrient enrichment of a waterbody, usually leading to growth and proliferation of plant material). See Table 4 for definitions of other trophic states in lakes.
<i>Hypolimnion</i>	The deepwater layer below the thermocline (see stratification) in a stratified lake.
<i>Littoral zone</i>	The shallow or inshore regions of a lake, defined as water shallow enough for the lake to be colonised by aquatic macrophytes.
<i>Monomixis</i> (<i>adj. monomictic</i>)	Mixing once a year. Water in monomictic lakes usually stratifies into layers over summer and mixes in autumn and winter. Most of the deeper lakes in New Zealand are monomictic.
<i>Oligotrophic</i>	Low in nutrients, hence with relatively low organic productivity; the opposite of eutrophic.
<i>Photic zone</i>	The surface waters of a lake where penetrating light has sufficient intensity to allow photosynthesis by aquatic plants.
<i>Polymixis</i> (<i>adj. polymictic</i>)	Frequent mixing; ie, lakes in which the water column undergoes frequent periods of stratification and re-mixing. Typical of shallow lakes, especially in lowland regions.
<i>Profundal zone</i>	The bottom of a deep lake, below the euphotic and littoral zones.
<i>Stratification</i>	Separation of layers of water in lakes because of different densities. Classically described from temperature effects, where water layers of approximately uniform temperature (the epilimnion and hypolimnion) are separated by a steep temperature gradient (the thermocline); it may also be driven by differences in salinity.

Appendix 2: Morphological and Catchment Characteristics of the 121 Lakes

Lake name	Region	Maximum depth (m)	Latitude	Longitude	Altitude (m)	Area (km ²)	Lake fetch (m)	Annual air temperature (°C)	Land cover	TLI
Alexandrina	Canterbury	27	5693438	2305464	711.09	6.46	6,811	8.5	Pasture	2.7
Benmore	Canterbury	120	5634947	2286478	346.51	75.85	15,996	8.1	Pasture	1.3
Brunner	West Coast	109	5841994	2382724	76.4	40.61	8,460	11.0	Native	3.3
Camp	Canterbury	13	5730709	2353070	675.94	0.44	1,275	8.7	Pasture	2.7
Carrot	Northland	3	6686569	2527949	54.98	0.02	370	15.7	Exotic forest	5.0
Clearwater	Canterbury	18	5731997	2352183	675	1.97	2,886	8.7	Native	3.2
Cococola (Rotopokaka)	Northland	3.5	6694458	2545805	1.97	0.12	650	16.0	Native	4.7
Coleridge	Canterbury	200	5767173	2388218	449.64	36.88	15,840	9.0	Native	1.2
Dunstan	Otago	60	5569628	2214738	188.02	26.73	8,484	8.6	Native	2.1
Ellesmere	Canterbury	2.1	5713381	2468141	16.59	197.81	25,008	11.8	Pasture	6.9
Emma	Canterbury	3	5728437	2357108	639.76	1.67	1,944	8.8	Pasture	3.9
Forsyth	Canterbury	4	5711625	2489581	2.63	5.59	4,922	11.5	Pasture	6.5
George	Southland	2	5415464	2114289	10.47	0.91	1,296	9.9	Pasture	4.3
Georgina	Canterbury	10	5764587	2393918	536.66	0.17	735	9.5	Pasture	2.9
Grassmere	Canterbury	15	5793167	2410195	589.18	0.62	1,534	9.1	Pasture	2.4
Hakanoa	Waikato	2.5	6403221	2701778	15.5	0.56	1,113	14.0	Pasture	6.7
Hawdon	Canterbury	4	5788633	2416383	571.06	0.35	1,026	9.2	Pasture	2.5
Hawea	Otago	384	5630626	2217057	283.16	151.77	24,256	7.5	Native	1.7
Hayes	Otago	35	5572345	2179434	324.78	2.74	3,050	9.8	Pasture	4.0
Heather	Northland	6	6683381	2528513	37.85	0.08	826	15.8	Pasture	4.3
Heron	Canterbury	37	5746534	2362643	692.39	6.95	5,428	8.5	Native	2.3
Horowhenua	Manawatu	1.8	6063883	2700697	19.93	3.04	3,078	12.8	Pasture	6.7
Humuhumu	Northland	15	6540962	2611441	51.05	1.40	1961	14.6	Exotic forest	4.1
Ida	Canterbury	9	5773663	2391294	675.65	0.10	735	8.8	Alpine	2.2
Jacks	Northland	6.5	6645327	2595284	116.99	0.16	624	14.9	Pasture	4.7
Johnson	Otago	27	5569585	2173614	391.2	0.25	969	9.5	Pasture	4.3
Kahuparere	Northland	7.5	6536283	2614438	57.5	0.07	420	14.5	Exotic forest	4.5
Kai-iwi	Northland	16	6598361	2569729	78.3	0.27	918	14.4	Native	3.7

Lake name	Region	Maximum depth (m)	Latitude	Longitude	Altitude (m)	Area (km ²)	Lake fetch (m)	Annual air temperature (°C)	Land cover	TLI
Kanono	Northland	14	6537016	2613250	57.29	0.77	1,425	14.5	Exotic forest	4.2
Kapoi	Northland	9	6572652	2585614	37.72	0.02	370	14.6	Pasture	6.7
Karaka7	Northland	5	6542655	2603865	5.92	0.11	539	14.8	Exotic forest	4.6
Katrine	Canterbury	28	5831848	2444415	519.88	0.78	1,666	9.0	Native	2.2
Kereta	Auckland	1.5	6511485	2624910	17.07	0.24	1,239	14.6	Pasture	4.3
Kihona	Northland	8.3	6730334	2502020	57.73	0.07	598	15.6	Exotic forest	4.3
Kuwakatai	Auckland	19	6518581	2621484	56.3	0.28	1,110	14.3	Pasture	5.5
Lady	West Coast	23	5843961	2393035	111.09	1.41	1,938	11.2	Native	3.3
Lyndon	Canterbury	28	5766406	2404487	825.96	0.88	2,256	7.5	Native	2.4
Mahinapua	West Coast	10	5821329	2339616	13.83	3.94	3,174	11.5	Native	3.4
Manapouri	Southland	444	5506686	2079928	141.64	141.78	26,999	7.8	Native	2.4
Maratoto	Waikato	7	6365957	2712868	56.08	0.18	756	13.5	Pasture	5.2
Midgeley	Northland	15	6590067	2574881	76.71	0.03	300	14.4	Pasture	4.5
Mokeno	Northland	5.5	6538876	2605741	8.31	1.59	2,730	14.7	Exotic forest	5.0
Morehurehu	Northland	14	6728865	2510606	16.97	0.36	1,200	15.8	Exotic forest	4.1
Ngakapua (North basin)	Northland	8.2	6686948	2528353	51.64	0.03	270	15.8	Exotic forest	4.5
Ngakapua (South basin)	Northland	5.2	6686889	2528576	56.19	0.06	720	15.7	Exotic forest	4.6
Ngakeketa North	Northland	7	6742798	2488764	55.96	0.11	570	15.5	Native	4.9
Ngakeketa South	Northland	8.7	6742636	2490006	38.14	0.11	731	15.6	Native	4.7
Ngaroto	Waikato	4	6358441	2711318	36.65	0.92	1,792	13.6	Pasture	6.3
Ngatu	Northland	6.5	6685531	2528923	37.4	0.52	1,323	15.9	Pasture	4.1
Ngatuwhetu	Northland	5.1	6735918	2500394	72.1	0.10	400	15.5	Pasture	4.1
Ohau	Canterbury	129	5658940	2259235	455.14	59.27	14,768	8.0	Native	1.4
Okareka	Bay of Plenty	33.5	6331329	2804548	344.39	3.34	2,793	12.0	Native	3.4
Okaro	Bay of Plenty	18	6317113	2806968	419.72	0.30	714	11.5	Pasture	6.0
Okataina	Bay of Plenty	78.5	6335922	2809199	302.04	10.73	6,096	11.7	Native	3.1
Ototoa	Auckland	29	6520426	2621349	76.31	1.07	2,021	14.3	Native	3.8
Pearson	Canterbury	17	5788399	2410832	603.15	2.02	3,648	8.9	Native	2.0
Poerua	West Coast	7.8	5832585	2386762	95.37	2.13	2,800	10.7	Native	3.1
Pretty	Northland	4.4	6735416	2495491	58.59	0.07	552	15.5	Exotic forest	3.5
Pukaki	Canterbury	70	5679850	2283162	477.64	172.74	31,164	9.1	Alpine	1.4
Pupuke	Auckland	57	6489737	2668039	14.17	1.04	1,421	15.0	Urban	4.3
Rerewhakaaitu	Bay of Plenty	15.8	6317066	2816346	438.74	5.17	3,650	11.3	Pasture	3.5
Reservoir	Southland	5	5387320	2207988	13.45	0.36	1,140	10.0	Pasture	4.5

Lake name	Region	Maximum depth (m)	Latitude	Longitude	Altitude (m)	Area (km ²)	Lake fetch (m)	Annual air temperature (°C)	Land cover	TLI
Rotoehu	Bay of Plenty	13.5	6347680	2820034	296.87	7.90	4,224	12.2	Native	4.5
Rotoiti	Bay of Plenty	126	6346199	2810076	270.4	33.69	10,526	12.4	Native	4.8
Rotokakahi	Bay of Plenty	32	6326415	2800852	386	4.33	4,368	11.3	Exotic forest	3.0
Rotokauri	Waikato	4	6380054	2703790	26.56	0.38	990	13.8	Pasture	6.2
Rotokawau	Northland	12	6686958	2529655	50.54	0.15	572	15.8	Exotic forest	4.3
Rotokawau	Northland	11	6538807	2613517	59.99	0.26	882	14.6	Exotic forest	3.9
Rotokawau East	Northland	2.5	6703212	2540157	7.74	0.24	624	16.0	Pasture	6.9
Rotokawau West	Northland	2.5	6703378	2539214	7.86	0.66	1,166	16.0	Pasture	6.5
Rotoma	Bay of Plenty	83	6344716	2824704	304.1	11.12	5,350	12.0	Native	2.5
Rotomahana	Bay of Plenty	125	6320694	2811331	333.17	9.02	6,084	11.8	Native	3.9
Rotomanuka	Waikato	4.8	6361528	2713710	58.28	0.14	620	13.4	Pasture	4.7
Rotoroa	Northland	8	6682525	2528712	32.64	0.28	1,344	15.8	Pasture	4.3
Rotoroa (Hamilton Lake)	Waikato	6.5	6375789	2710488	38.1	0.52	1,344	13.6	Urban	4.7
Rotorua	Canterbury	3	5866690	2557903	27.53	0.43	1,224	12.4	Native	6.6
Rotorua	Bay of Plenty	44.8	6341883	2797129	270.02	80.48	11,907	12.6	Pasture	4.9
Rototuna	Northland	5	6549477	2604043	118.56	0.09	470	14.2	Exotic forest	4.7
Ryan	West Coast	3	5863058	2362490	3.04	0.03	390	11.9	Pasture	5.1
Sarah	Canterbury	6.7	5794662	2410313	575.37	0.22	750	9.2	Pasture	2.6
Selfe	Canterbury	30	5773127	2389692	568.66	0.65	2,046	8.9	Pasture	2.2
Serpentine	Waikato	4	6358905	2713936	57.82	0.04	408	13.4	Pasture	5.0
Ship Creek	West Coast	3	5708430	2199322	2.51	0.10	910	11.3	Native	2.7
Spectacle	Auckland	7	6556391	2657343	16	0.44	945	15.4	Pasture	6.4
Sumner	Canterbury	134.5	5833483	2445793	504.71	13.73	9,216	8.6	Native	1.4
Taharoa	Northland	37	6599239	2569199	78.4	2.04	2,205	14.4	Native	2.5
Tarawera	Bay of Plenty	87.5	6327992	2810620	278.48	41.15	10,481	11.7	Native	2.9
Taupo	Waikato	162.8	6263510	2761466	257.06	612.64	39,955	11.7	Native	2.2
Taylor	Canterbury	40.5	5826358	2447313	578.5	2.07	3,127	8.9	Native	2.1
Te Anau	Southland	417	5541983	2096331	169.44	342.97	32,508	7.4	Native	2.5
Te Kahika	Northland	11	6730838	2510898	15.59	0.14	782	15.9	Exotic forest	3.8
Tekapo	Canterbury	120	5698996	2310979	685.79	96.59	25,400	8.3	Alpine	2.0
Tikitapu	Bay of Plenty	27.5	6328765	2801872	414.33	1.44	1,696	11.6	Native	3.2
Tomahawk Lagoon #1	Otago	1.2	5475687	2319164	14.35	0.19	918	10.8	Pasture	5.4
Tomahawk Lagoon #2	Otago	1.2	5475623	2319795	14.99	0.10	636	10.7	Pasture	5.4
Tomarata	Auckland	5	6555045	2658951	32.63	0.14	600	15.4	Pasture	4.4

Lake name	Region	Maximum depth (m)	Latitude	Longitude	Altitude (m)	Area (km ²)	Lake fetch (m)	Annual air temperature (°C)	Land cover	TLI
Tuakitoto	Otago	3	5437554	2264835	21.03	1.32	2,200	10.2	Pasture	5.1
Vincent	Southland	5	5393554	2189821	19.16	0.17	1,014	10.0	Pasture	3.5
Waahi	Waikato	5	6402639	2697913	13.09	4.45	3,082	14.1	Pasture	6.2
Wahakari	Northland	12	6727765	2504015	53.47	0.84	1,643	15.6	Exotic forest	3.8
Waihola	Otago	2.2	5461436	2283720	12.36	6.08	5,700	10.1	Pasture	4.3
Waihopo	Northland	3	6716204	2514871	35.02	0.03	320	15.8	Exotic forest	4.3
Waikare	Waikato	1.8	6415678	2705039	6.76	34.37	9,796	14.1	Pasture	7.1
Waikere	Northland	30	6600154	2567597	91.04	0.30	832	14.3	Pasture	3.6
Waimimiha	Northland	2	6672922	2526359	11.94	0.10	590	15.8	Pasture	6.5
Wainamu	Auckland	15	6478113	2641296	36.36	0.15	936	14.2	Native	4.4
Waingata	Northland	7	6538308	2613841	57.28	0.11	572	14.5	Pasture	5.3
Wainono Lagoon	Canterbury	3	5610345	2363907	5.42	3.99	4,324	11.1	Pasture	5.9
Wainui	Northland	11.8	6566357	2590008	40.26	0.04	410	14.6	Pasture	5.6
Waipara/Dead	Northland	10	6735082	2497639	77.12	0.02	290	15.5	Exotic forest	4.2
Waiparera	Northland	6	6695240	2527412	31.26	1.09	1,450	15.9	Exotic forest	4.8
Waipori	Otago	1	5467048	2286029	7.25	1.84	1,974	10.3	Native	4.7
Waiporohita	Northland	3	6699999	2542715	14.27	0.07	350	16.0	Pasture	6.6
Wairarapa	Wellington	2.5	5996166	2697717	1.26	77.37	17,888	12.6	Pasture	5.3
Wairere	Northland	5	6546950	2601783	11.77	0.11	736	14.6	Exotic forest	5.6
Waituna Lagoon	Southland	5	5395486	2172526	2.12	13.59	9,650	10.2	Pasture	4.5
Wakatipu	Otago	380	5561667	2160117	237.03	298.25	29,708	7.0	Native	2.3
Wanaka	Otago	311	5624063	2201051	233.74	204.00	33,411	8.5	Native	1.9
Whakaneke	Northland	5	6536507	2605846	7.72	0.09	470	14.7	Exotic forest	6.6
Whangape	Waikato	3.5	6412806	2691846	17.07	10.79	5,376	14.2	Pasture	6.8
Wilkie	Otago	3	5397118	2236814	20	0.01	170	10.0	Native	4.4

Notes: Latitude and longitude in New Zealand map grid units. Land cover is dominant catchment land use type mapped from LCDB2. TLI is three-year average from 2004 to 2006.

Appendix 3: Maps of Water Quality Parameters

Figure A1: Trophic level index – North Island

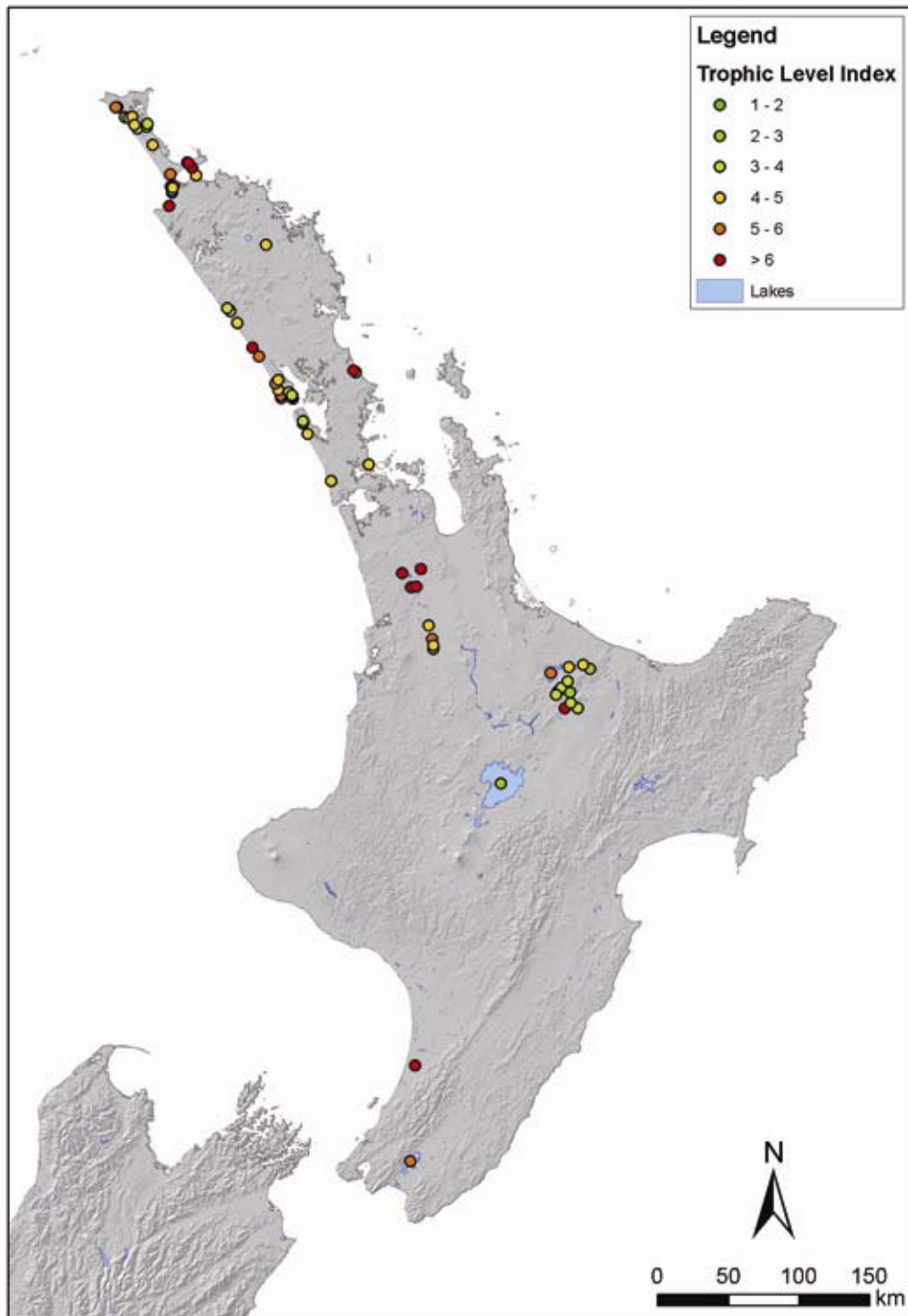


Figure A2: Trophic level index – South Island

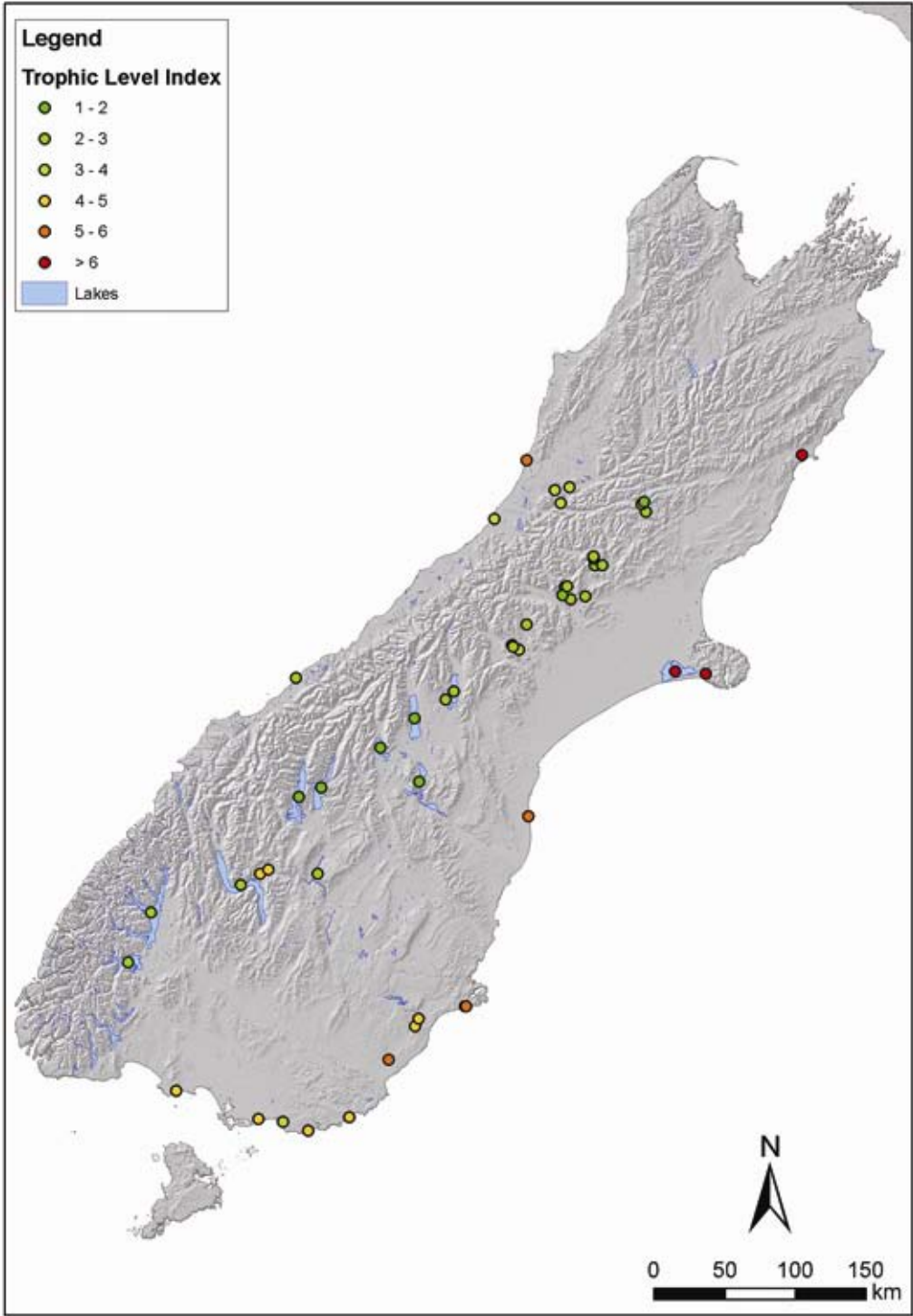
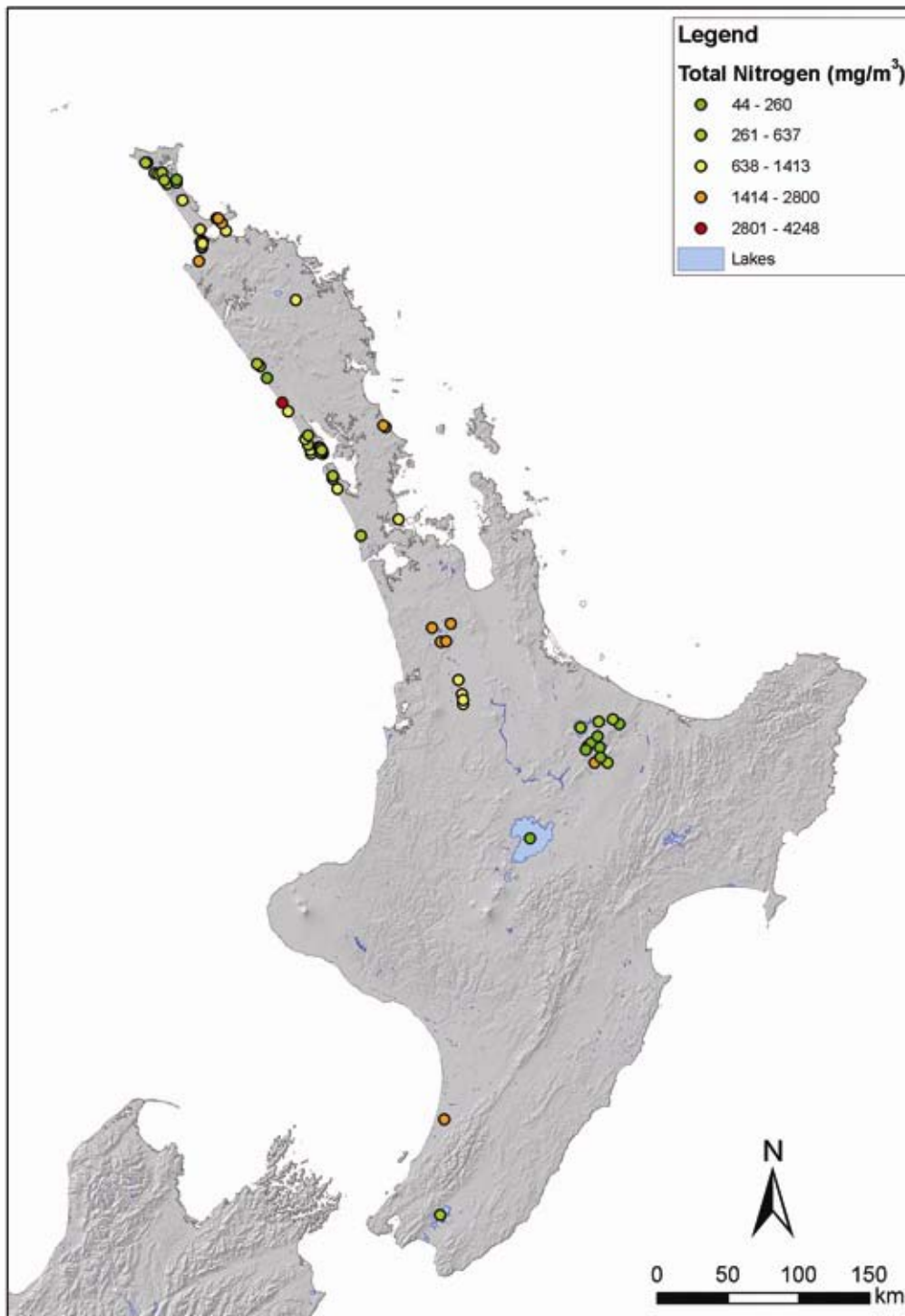
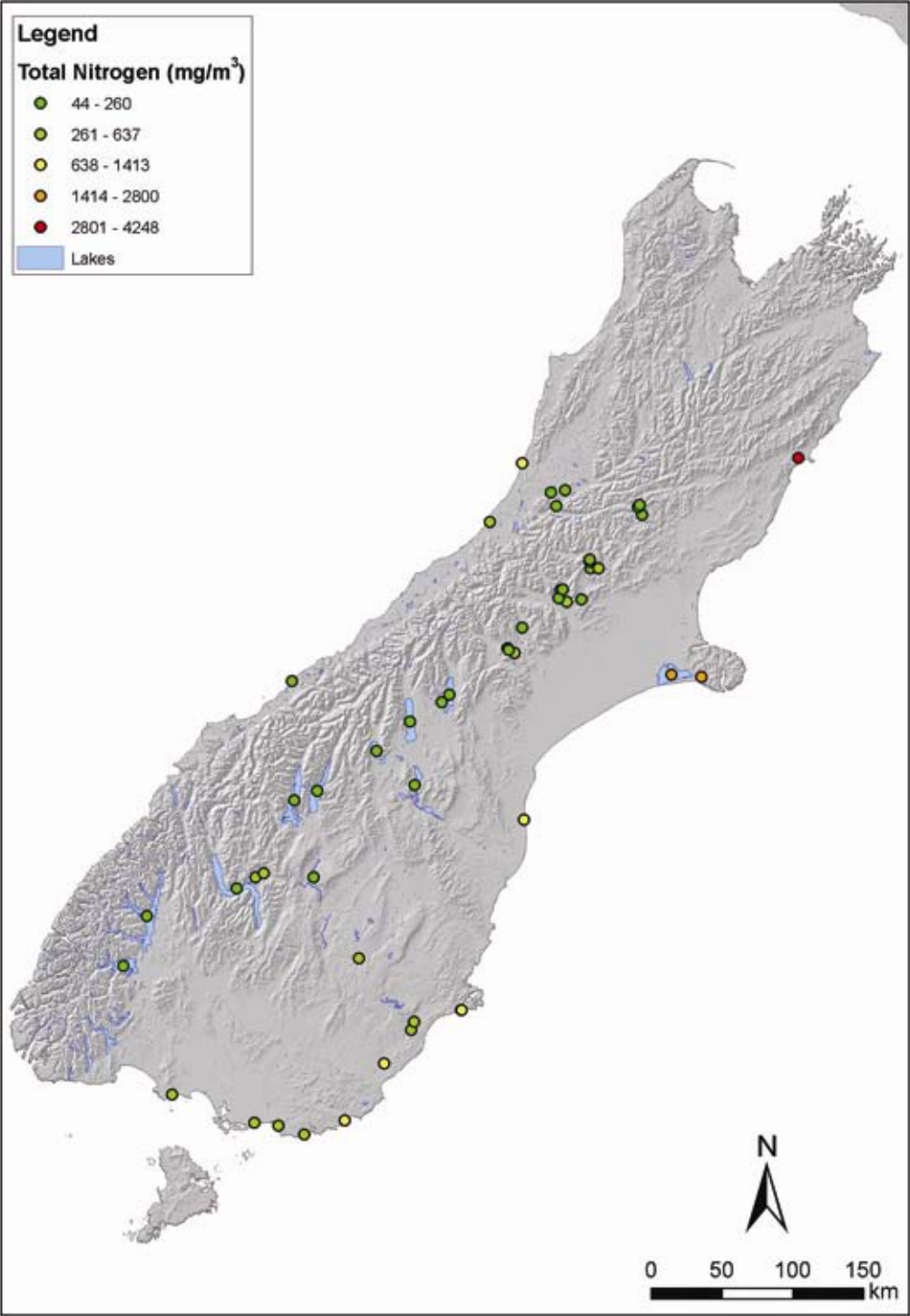


Figure A3: Total nitrogen – North Island



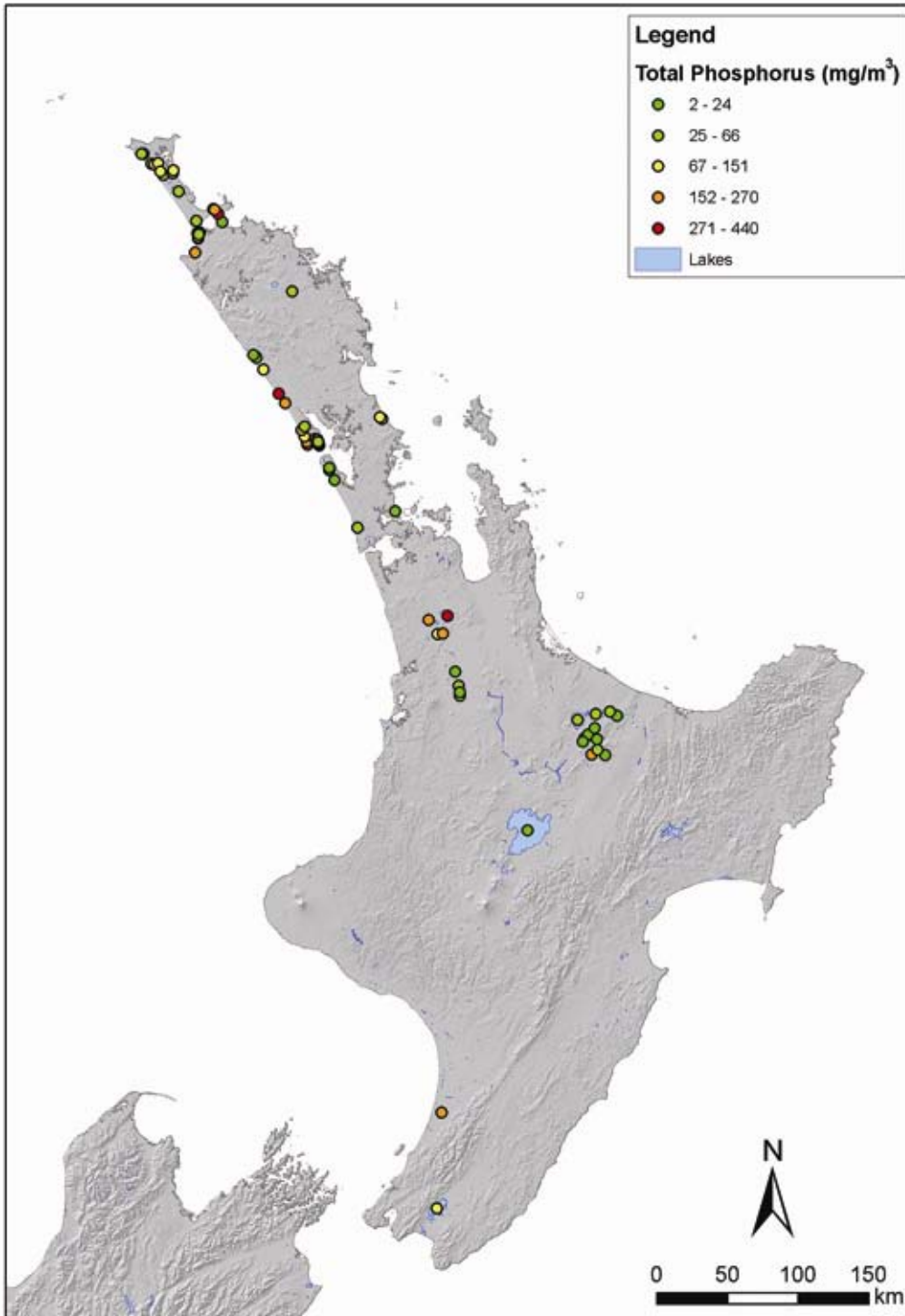
Data ranges for groups are generated automatically by natural breaks (Jenks) method in ESRI Arc GIS, a method that groups data (ie, lakes) into clusters of similar value.

Figure A4: Total nitrogen – South Island



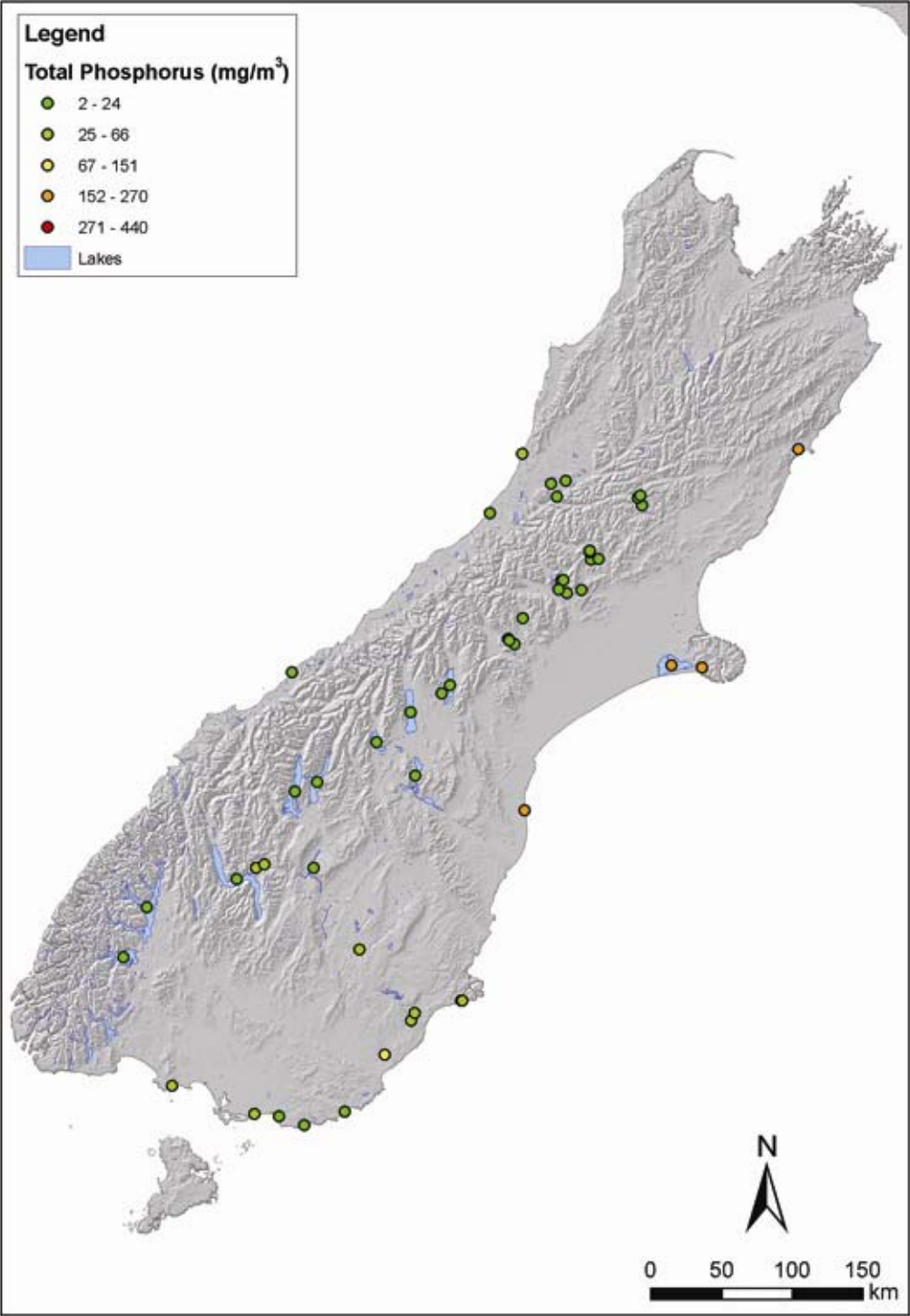
Data ranges for groups are generated automatically by natural breaks (Jenks) method in ESRI Arc GIS, a method that groups data (ie, lakes) into clusters of similar value.

Figure A5: Total phosphorus – North Island



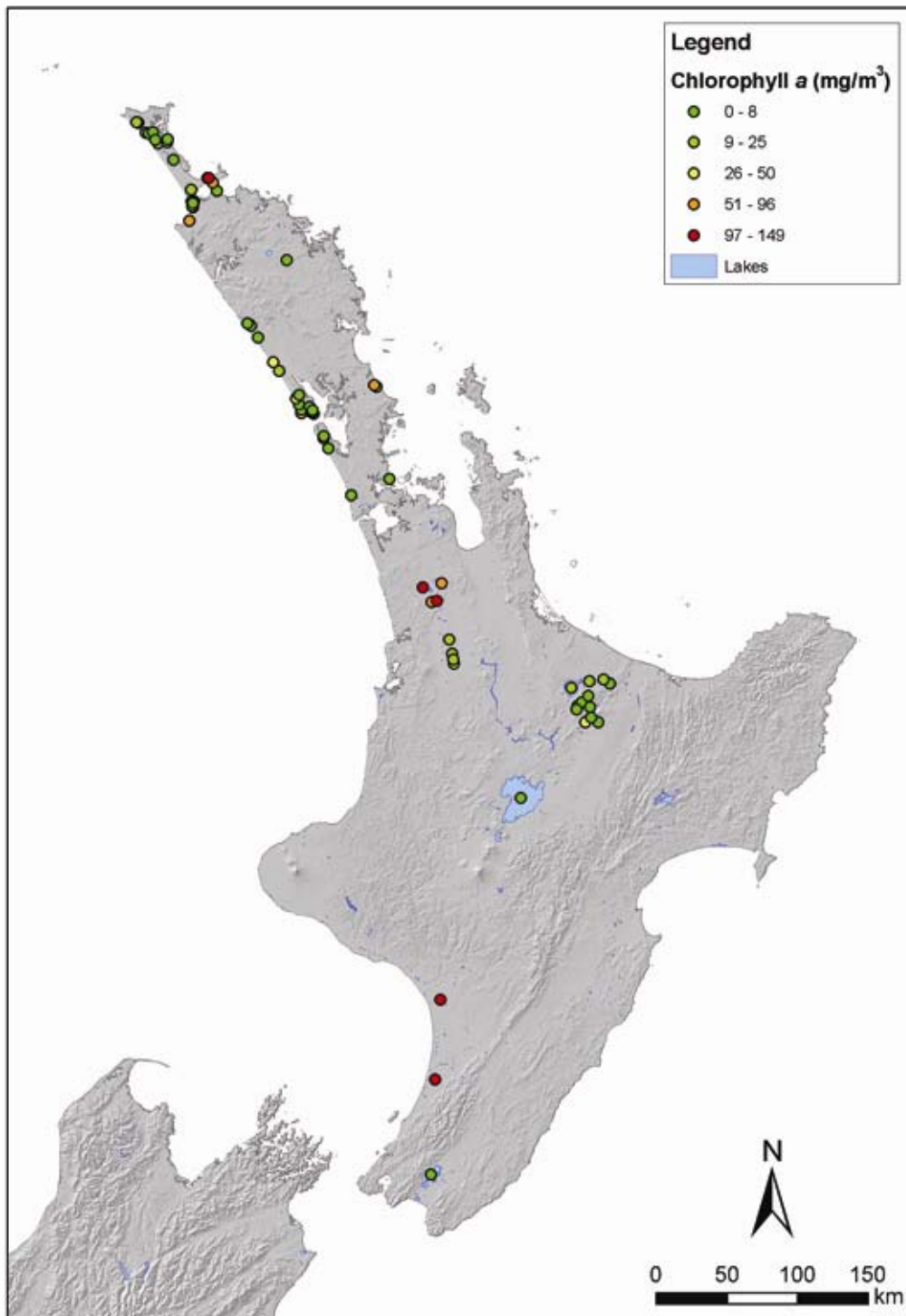
Data ranges for groups are generated automatically by natural breaks (Jenks) method in ESRI Arc GIS, a method that groups data (ie, lakes) into clusters of similar value.

Figure A6: Total phosphorus – South Island



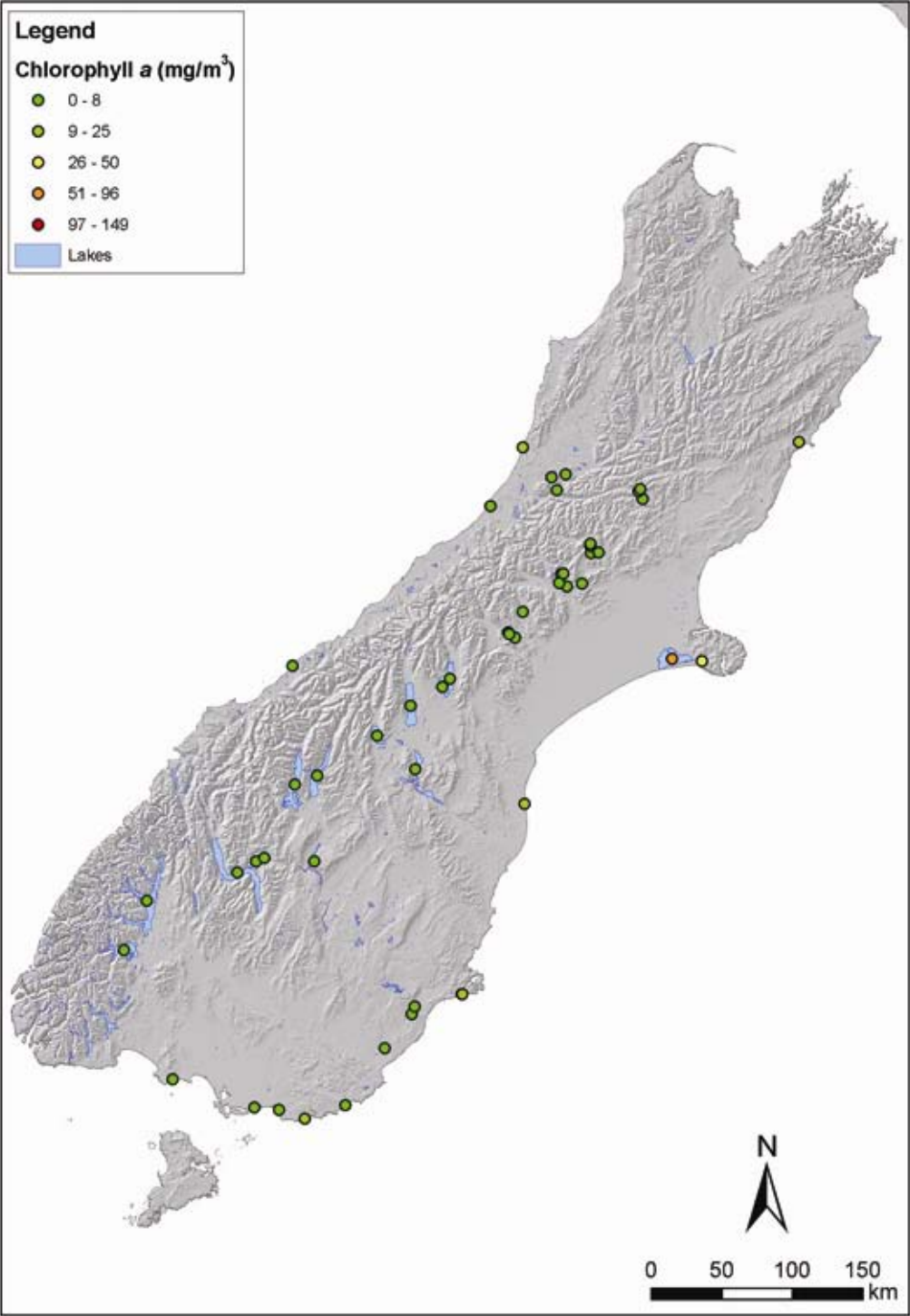
Data ranges for groups are generated automatically by natural breaks (Jenks) method in ESRI Arc GIS, a method that groups data (ie, lakes) into clusters of similar value.

Figure A7: Chlorophyll – North Island



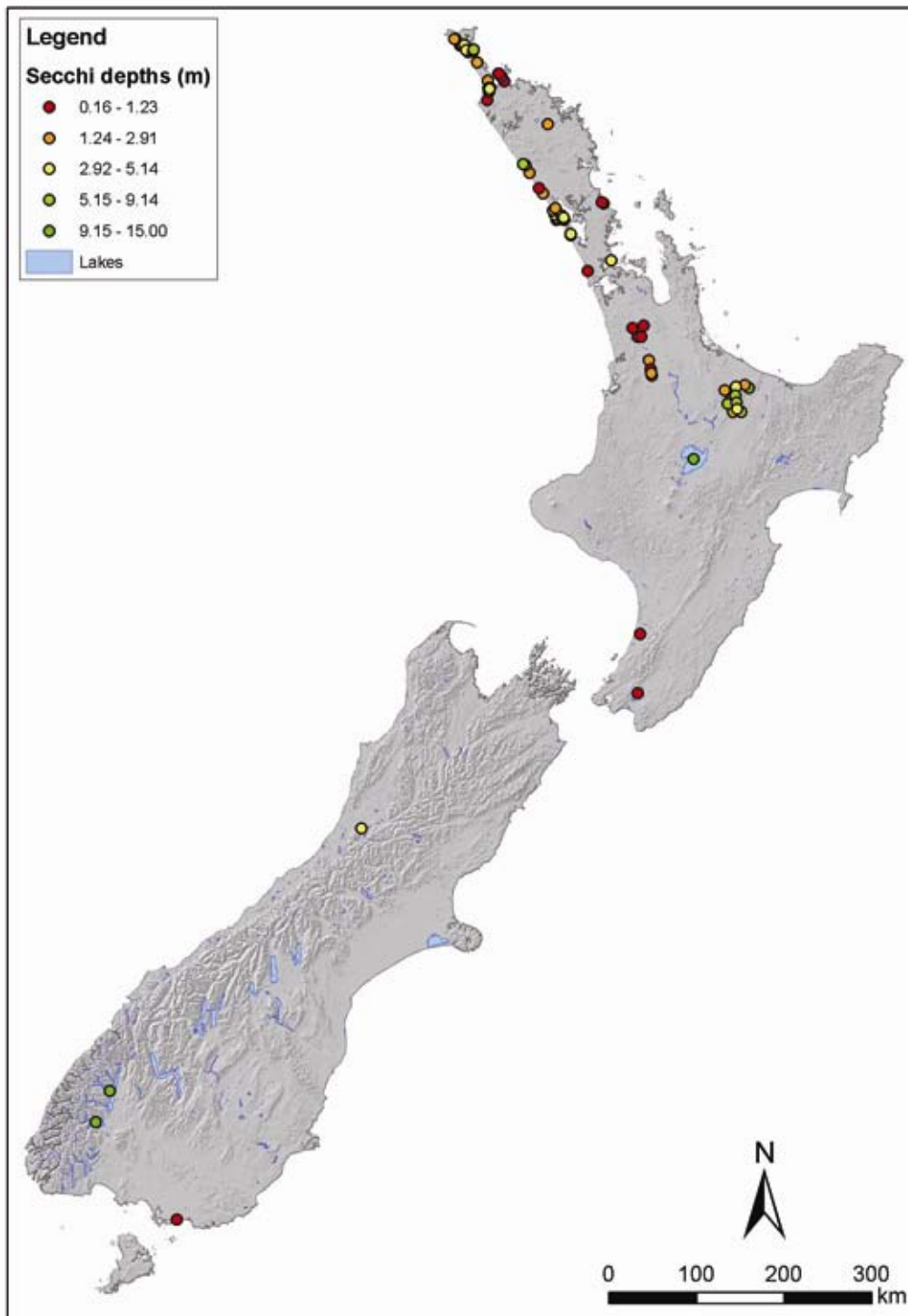
Data ranges for groups are generated automatically by natural breaks (Jenks) method in ESRI Arc GIS, a method that groups data (ie, lakes) into clusters of similar value.

Figure A8: Chlorophyll – South Island



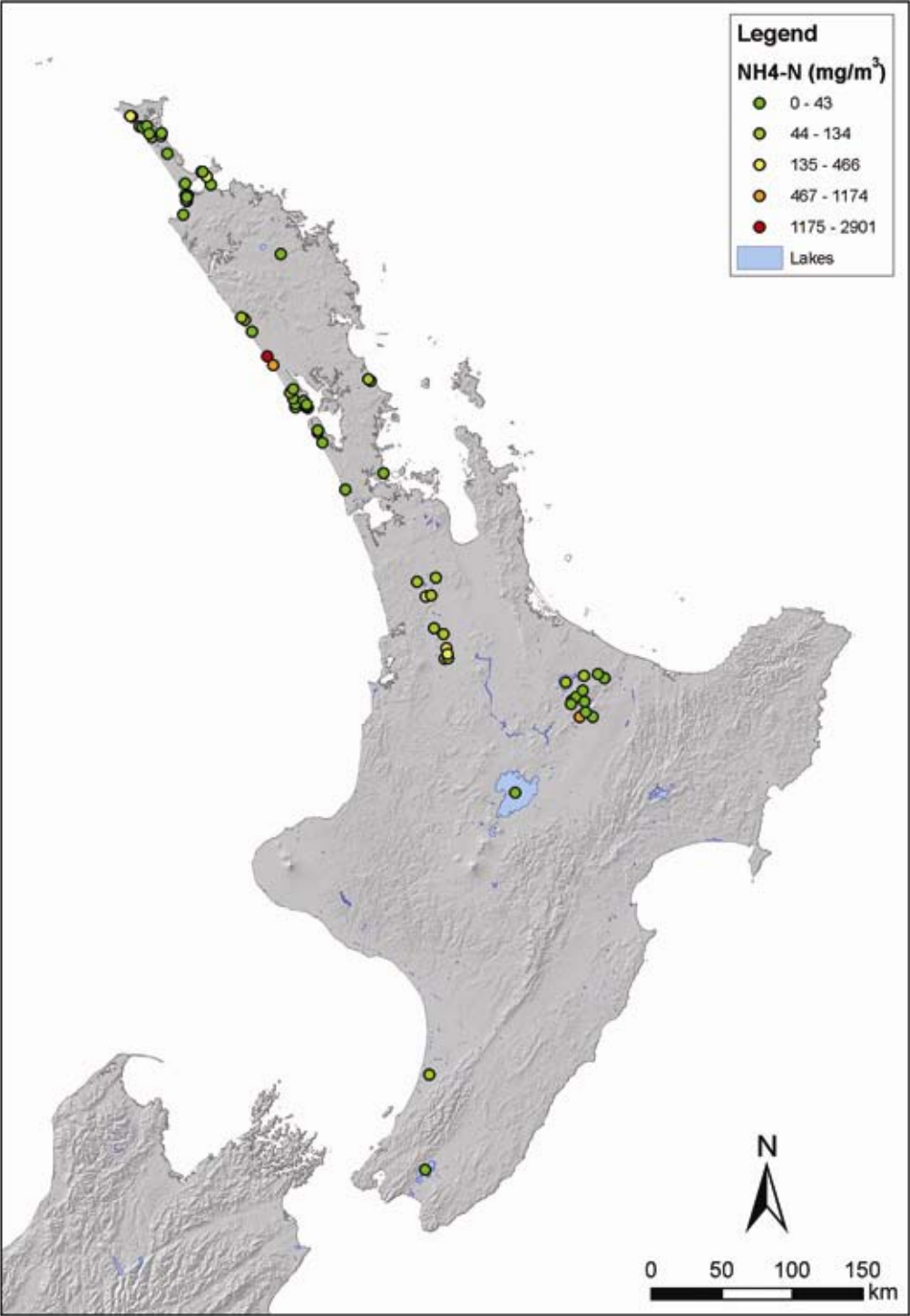
Data ranges for groups are generated automatically by natural breaks (Jenks) method in ESRI Arc GIS, a method that groups data (ie, lakes) into clusters of similar value.

Figure A9: Secchi depths



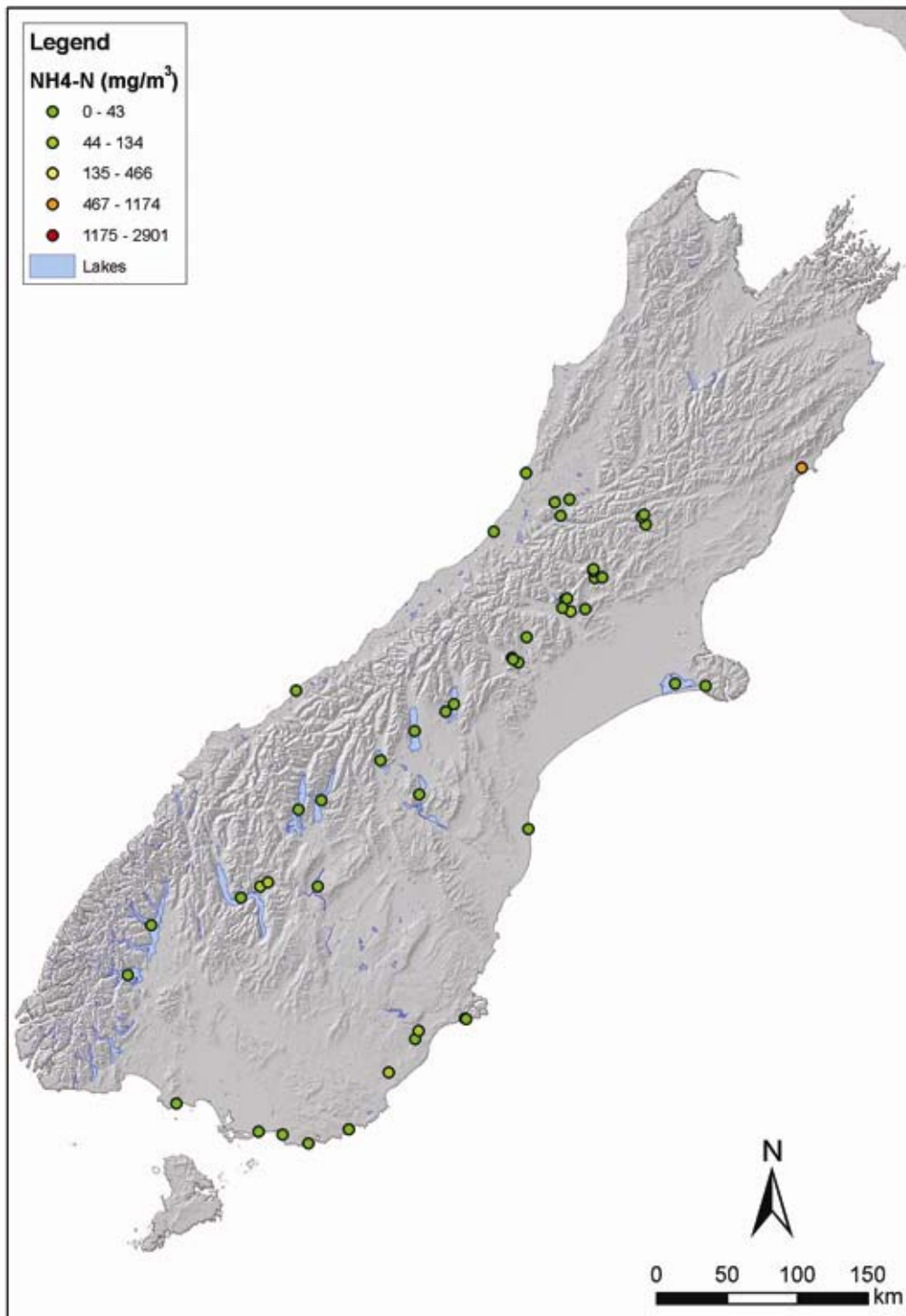
Data ranges for groups are generated automatically by natural breaks (Jenks) method in ESRI Arc GIS, a method that groups data (ie, lakes) into clusters of similar value.

Figure A10: NH4-N – North Island



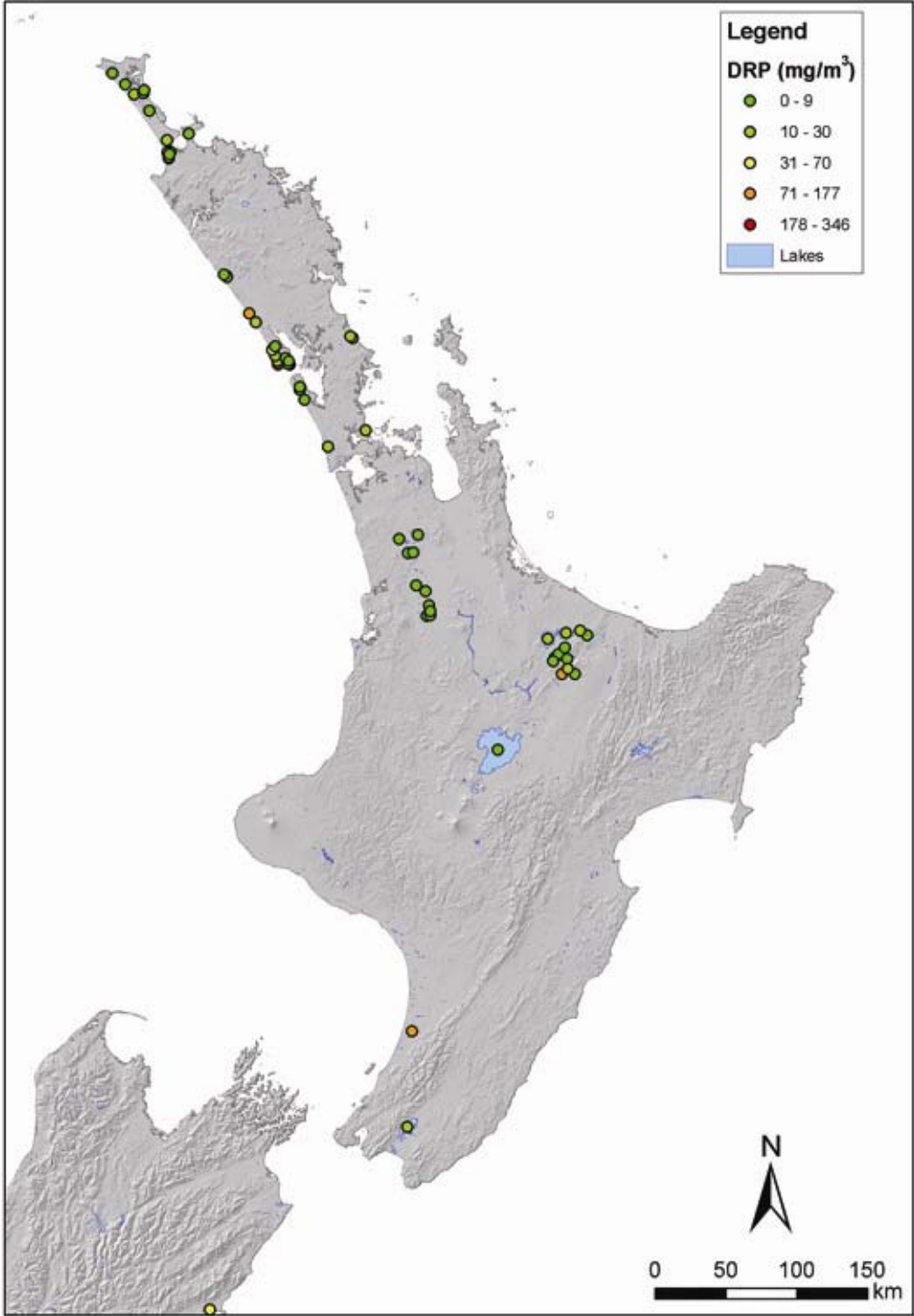
Data ranges for groups are generated automatically by natural breaks (Jenks) method in ESRI Arc GIS, a method that groups data (ie, lakes) into clusters of similar value.

Figure A11: NH4-N – South Island



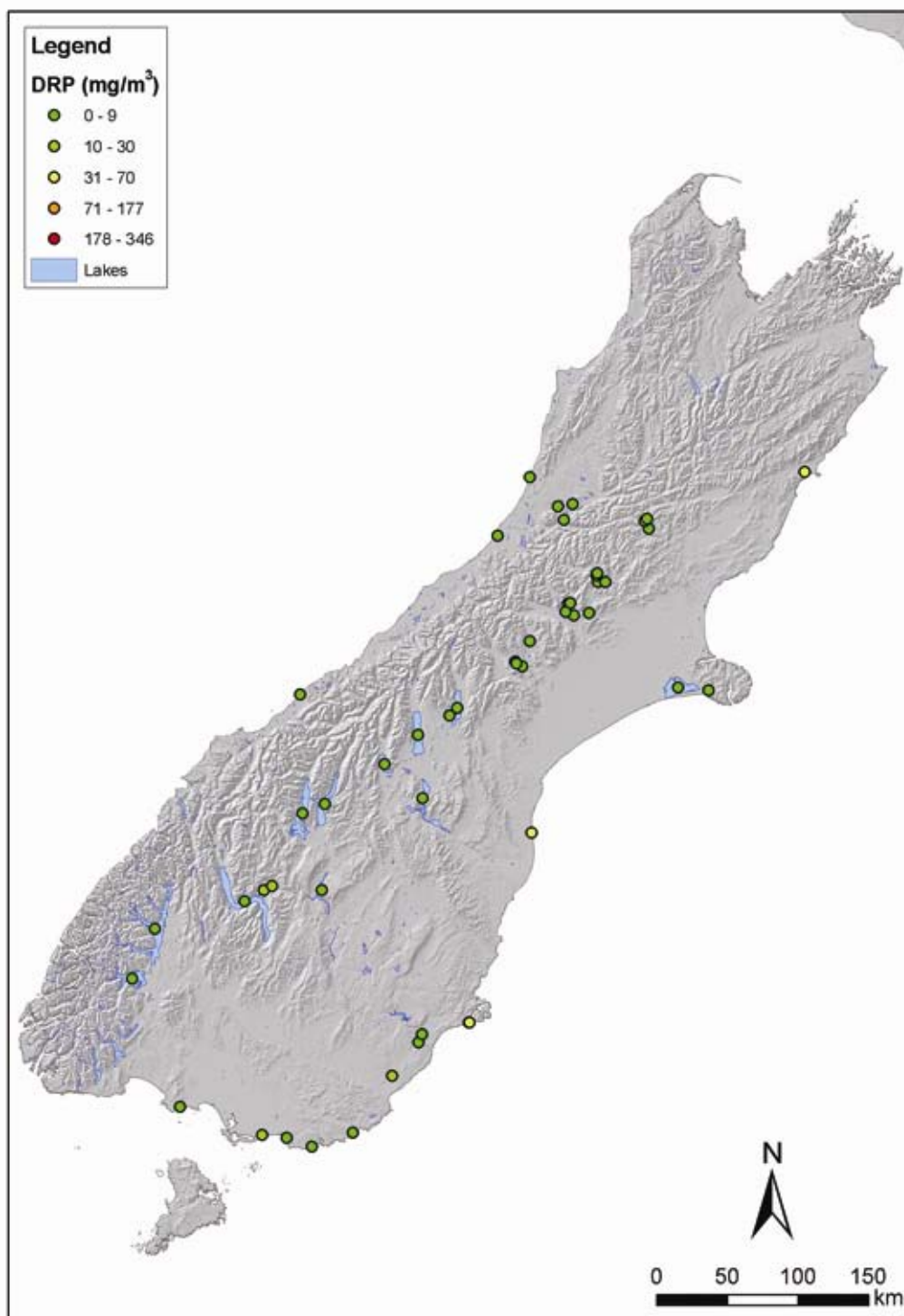
Data ranges for groups are generated automatically by natural breaks (Jenks) method in ESRI Arc GIS, a method that groups data (ie, lakes) into clusters of similar value.

Figure A12: DRP – North Island



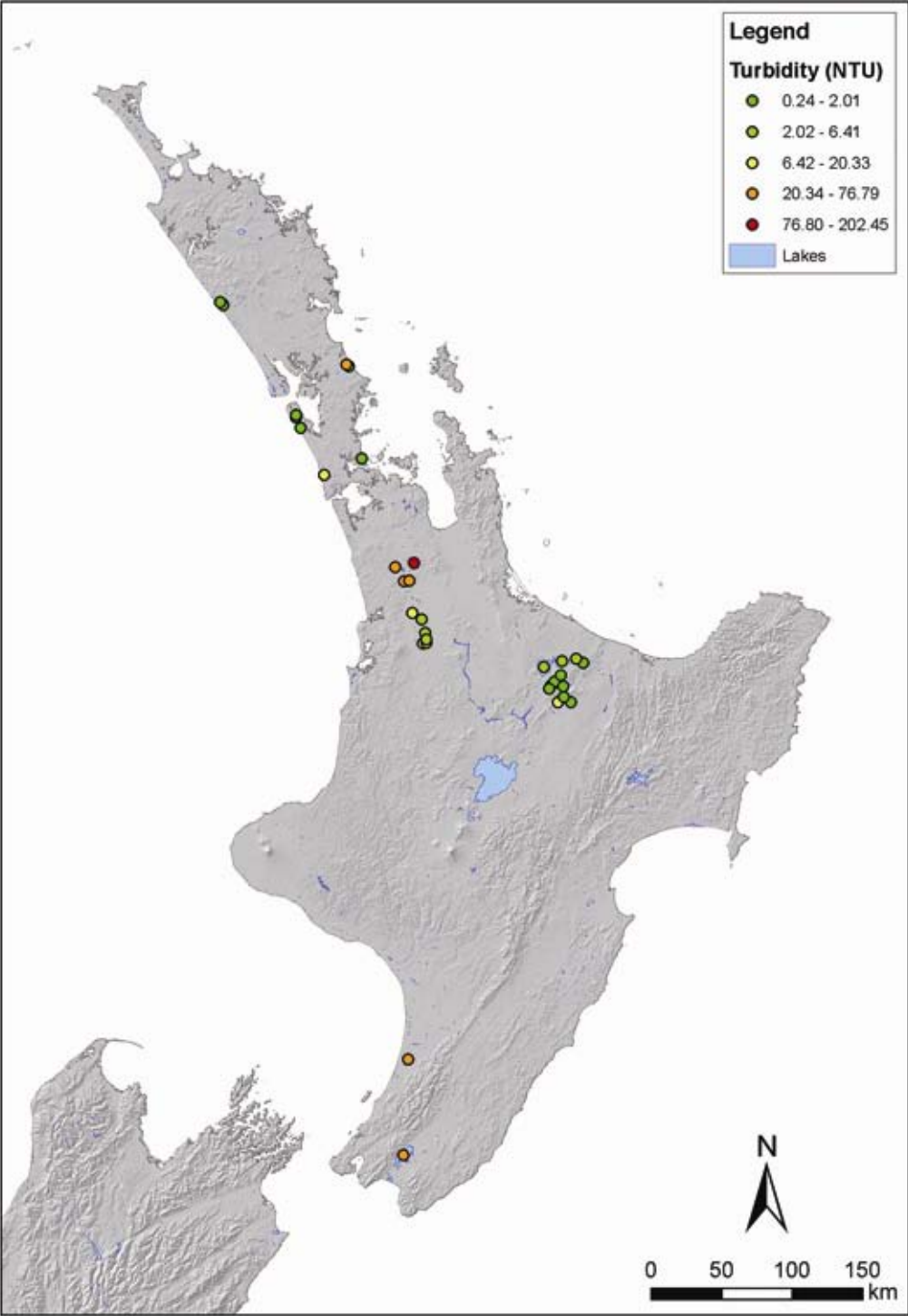
Data ranges for groups are generated automatically by natural breaks (Jenks) method in ESRI Arc GIS, a method that groups data (ie, lakes) into clusters of similar value.

Figure A13: DRP – South Island



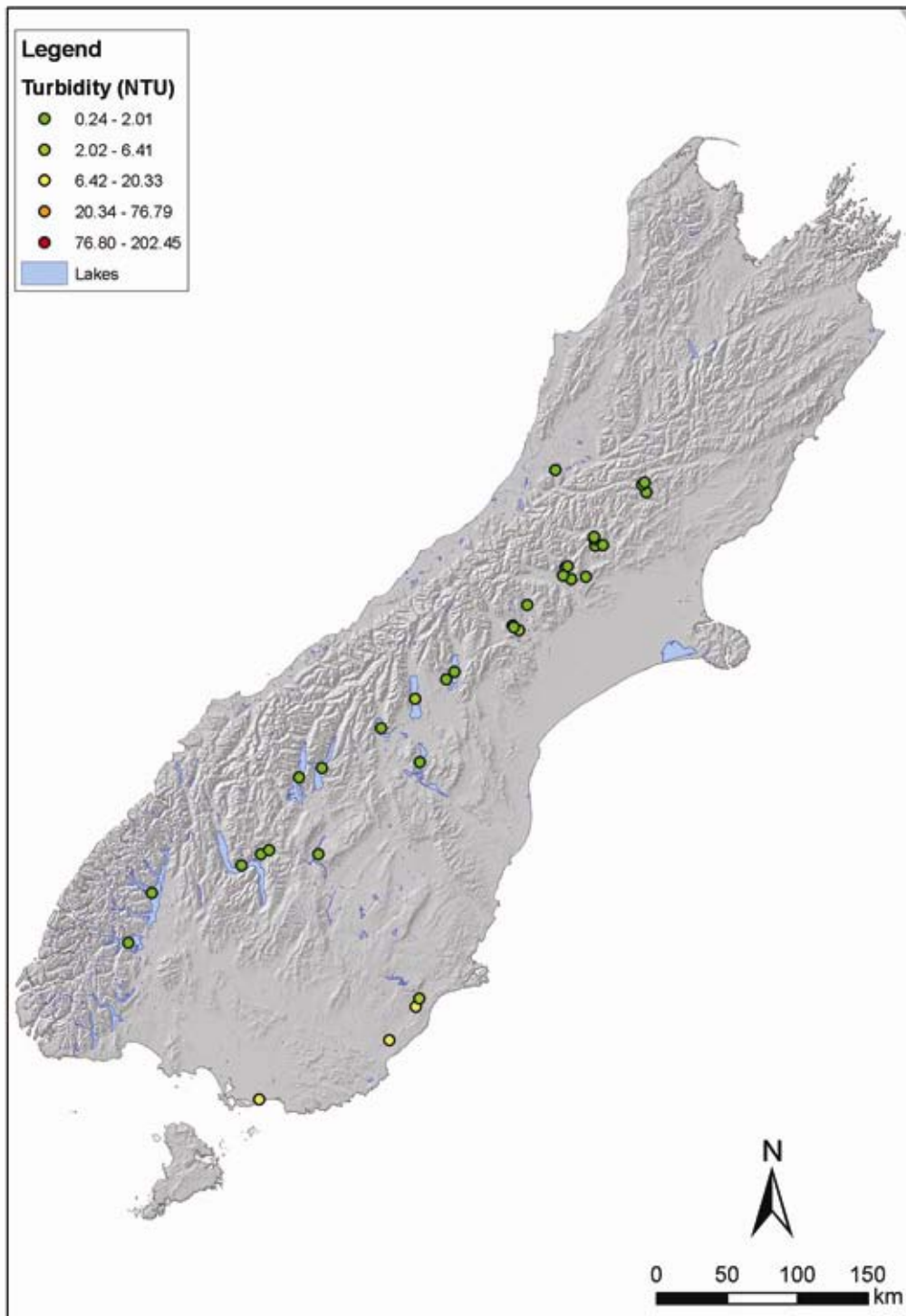
Data ranges for groups are generated automatically by natural breaks (Jenks) method in ESRI Arc GIS, a method that groups data (ie, lakes) into clusters of similar value.

Figure A14: Turbidity – North Island



Data ranges for groups are generated automatically by natural breaks (Jenks) method in ESRI Arc GIS, a method that groups data (ie, lakes) into clusters of similar value.

Figure A15: Turbidity – South Island



Data ranges for groups are generated automatically by natural breaks (Jenks) method in ESRI Arc GIS, a method that groups data (ie, lakes) into clusters of similar value.

Appendix 4: Map of Water Quality Trends (1990-2006) based on Percent Annual Change (PAC) using the Burns et al (2000) Methodology

Figure A16: PAC trend – North Island

