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Southland Water 2010: Our Ecosystems Technical Report for lakes and lagoons

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Prepared for
Environment Southland

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Executive Summary

Environment Southland, in collaboration with Te Ao Marama Inc is preparing reports on the state of the Southland freshwater environment. This technical report describes the state and trends in lake and lagoon water quality in Southland and will contribute to the lakes and lagoons section of Southland Water 2010: Our Ecosystems.

State of lake water quality

The key points about the state of water quality in Southlands lakes are:

- Regular water quality monitoring occurs in three lakes: Lake Te Anau, Lake Manapouri, and Waituna Lagoon;

- Lake Te Anau and Manapouri have very clean water and are classified as 'microtrophic' to 'oligotrophic'. Their water quality is in the top 10% of lakes monitored in New Zealand.

- Waituna Lagoon has high nutrient levels and is classified as 'eutrophic'. The estimated median Secchi depth in the lagoon breaches the Water Plan standard. However, median chlorophyll *a* concentrations meet the standard. Chlorophyll *a* concentrations are relatively low compared to the nutrient concentrations, suggesting that some other factor(s) is limiting the amount of algae growth in the lagoon.

- The CCME Water Quality Index classified the east, south and centre sites in Waituna Lagoon as "Fair" (i.e. conditions sometimes depart from desirable levels), but the west site as classified as "Marginal" due to a single failure of pH against the Water Plan standard.

- Historic spot sampling of other small coastal lakes (Forest Lake, Lake George, Lake Vincent and the Reservoir) indicate that these small coastal lakes are in a eutropic to supertrophic condition, with high concentrations of nutrients.

- Water quality monitoring results from Lake Te Anau and Lake Manapouri have a large number of samples recorded as 'below detection'. The large number of these non-detect samples present a problem for accurately assessing the state of the lake and seriously limits the ability of the monitoring to detect water quality trends. Recommendations are made to improve the monitoring methods.

- The deep water sites monitored on Lake Te Anau and Lake Manapouri are stratified for about 33% and 44% of the time respectively. The lowest dissolved oxygen recorded in the bottom waters when these lakes are stratified are 8.4 g/m^3 and 6.5 g/m^3 for Lake Te Anau and Lake Manapouri respectively.

- Ecological condition has been assessed in six southland lakes using LakeSPI. All were natural state lakes in Fiordland and all had 'high' LakeSPI scores (i.e. 50%-75%). This puts them in the top one third of NZ lakes.

- All major water quality variables in the Waituna Lagoon (e.g. total nitrogen, total phosphorus, chlorophyll *a*, electrical conductivity, turbidity) responded to whether it was open or closed. The strongest impact of opening or closing the lagoon was on salinity, electrical conductivity, total nitrogen, and the trophic level index.

- Open Waituna Lagoon to the sea results in an improvement in water quality however, care is needed to ensure that any change in the opening regime to improve water quality does not result adversely affect germination of *Ruppia* sp. the lagoon.

Trends in lake water quality

Lake water quality data was analysed for trends using a seasonal Kendall test. Water quality data from Waituna Lagoon was adjusted to account for when the lagoon was open or closed. The trend analysis found:

Lake Manapouri:

- A strong decreasing (deteriorating) trend in Secchi depth since about 2005. This is possibly part of a cyclic pattern but should be carefully monitored in case it is due to external pressures.

- A change in detection limits have caused artificial trends in TP and probably turbidity.

- There is a limited ability to detect trends due to a large number of values below detection limit, consequently trends could be occurring without being detected.

Lake Te Anau

- A downward (improving) trend in TN at both Blue Gum Point and in South Fiord.

- A change in detection limits have caused artificial downward trend in TLI (South Fiord) and probably turbidity.

- There is a limited ability to detect trends due to a large number of values below detection limit, consequently trends could be occurring without being detected.

Waituna Lagoon

- An increasing (deteriorating) trend in TP at Waituna Lagoon sites Centre (before and after turbidity adjustment) and West (after turbidity adjustment). This is concerning because Waituna Lagoon is probably P limited and it should be carefully monitored.

- A downward (improving) trend in chlorophyll *a* at Waituna Lagoon sites south and West was apparent after adjusting data for open and closed regime. Blooms of macroalgae (attached to sediments and plants) have been recorded in recent years (i.e. 2009 and 2010) and this may have suppressed the growth of planktonic algae (and chlorophyll *a* concentrations) by competing for nutrients.

- More periods of lagoon closure since ~2006 have caused an apparent increase (deterioration) in TN.

- Concentrations of nitrate during winter have increased at some sites, independent of the ‘open and closed’ regime. Summer nitrate concentrations are still often low, probably due to plant and algae utilisation.

- Maintaining at least monthly sampling of Waituna Lagoon is important to ensure any trend analysis has sufficient power after making other adjustments (e.g. for EC, turbidity or 'open and closed' regime).

Could Waituna Lagoon 'Flip'?

Waituna Lagoon is dominated by the native aquatic plants (macrophytes) *Ruppia* sp and *Myriophyllum triphyllum. Ruppia* sp. in particular is a keystone species in Waituna Lagoon because of its importance as a habitat for invertebrates and fish, as a food source for invertebrates and waterfowl, and because of its role in regulating water quality by stabilising the sediments, and reducing turbulence.

In some lakes this state of having clear water in a macrophyte dominated lake suddenly changes in a phenomenon known as lake flipping. When a lake flips, it undergoes a regime shift from a macrophyte-dominated clear water state to a de-vegetated, turbid water state. At least 37 lakes in New Zealand that have undergone a lake flip between clear water and turbid states and/or vice versa (Schallenberg and Sorrell 2009). A collapse of the macrophyte community is followed by deterioration in water quality (Hamill 2006).

In the turbid state, light penetration is limited, preventing macrophytes from establishing again, allowing continued re-suspension of sediment by wave energy, which exacerbates the poor light penetration. Sediment resuspension from the bottom also increase the loading of phosphorus and nitrogen in the water column, potentially favouring phytoplankton growth over macrophytes.

Waituna Lagoon has estimated water clarity (Secchi depth) of about 1.2m, which is not sufficient for light to reach the bottom of the deepest parts of the lagoon. A decline in water clarity could impact on the cover of *Ruppia* sp. in deeper parts of the lagoon with the potential for this to cause the lagoon to flip to a turbid state. If this were to occur it could mean the loss of aquatic plants (*Ruppia sp*.) and relatively clear water, as the water becomes increasingly turbid with suspended sediment and phytoplankton.

The likelihood of Waituna Lagoon exhibiting a regime shift was assessed using the relationship between land use variables and % regime-shifting lakes developed by Schallenberg and Sorrell (2009). This predicted that the likelihood of Waituna Lagoon flipping would double to almost 80% if the % pasture in the catchment increased from its current 65% cover to 71% cover.

The likelihood of Waituna Lagoon flipping may significantly increase if the trend of increasing phosphorus concentrations continues. It could also increase if:

- There was an increase in the percentage of pasture in the catchment, an increase in the intensity of land use or a loss of native plant cover resulting in increased loads of nutrient or sediments;

- The extent of native macrophyte cover was reduced by changes in the salinity or light regime;

- The lagoon was invaded by exotic macrophytes;

- The lagoon or upstream catchment was invaded by coarse fish species (e.g. catfish, goldfish, rudd, tench, or koi carp).

1 Introduction

1.1 Background

Environment Southland, in collaboration with Te Ao Marama Inc is preparing reports on the state of the Southland freshwater environment (Southland Water 2010). The main focus for Water 2010 is the state of the water quality and quantity within Southland.

The Water 2010 report will be based on the Regional Water Plan for Southland, to enable the findings to have direct management relevance. It will consist of four separate reports, with Ngai Tahu ki Murihiku cultural values incorporated within each report. The four reports will cover:

- Our Health (already published)
- Our Uses
- Our Ecosystems
- Our Threats (Natural Hazards).

Opus International Consultants was contracted to provide a technical report and advice for the lakes and lagoons section of Southland Water 2010: Our Ecosystems. This technical report describes the state and trends in lake and lagoon water quality in Southland and makes comparisons to management standards. It also provides a stand-alone discussion on ‘lake flipping’ and its relevance in relation to Waituna Lagoon.

1.2 Management framework and water quality standards in the Water Plan

The Southland Regional Water Plan (RWP) sets different management standards for lakes according to their location in lowland areas, hill country areas, mountain areas or whether they are classified as ‘natural state’.

Waituna Lagoon falls within the classification of “lowland coastal lakes and wetlands”. The RWP standards (abridged) set for lowland coastal lakes is:

> *“The temperature of the water: ... shall not exceed 23°C ....*
>
> *The pH of the water shall be within the range 6.5 to 9, and there shall be no pH change in water due to a discharge that results in a loss of biological diversity or a change in community composition.*
>
> *The concentration of dissolved oxygen in water shall exceed 80% of saturation concentration.*
>
> *There shall be no bacterial or fungal slime growths visible to the naked eye as obvious plumose growths or mats....*
>
> *When lake inflows are below their median values, the Secchi depth clarity of the water shall not be less than 1.5 metres, except where the water is naturally low in clarity as a*

> *result of high concentrations of tannins, in which case the natural colour and clarity shall not be altered.*
>
> *The concentration of total ammonia shall not exceed the values specified in Table 1 "Ammonia standards for Lowland and Hill surface water bodies".*
>
> *The concentration of faecal coliforms shall not exceed 1,000 coliforms per 100 mL, except for popular bathing sites, defined in Appendix K "Popular Bathing Sites", where the concentration of Escherichia coli shall not exceed 130 E. coli per 100 mL.*
>
> *The concentration of chlorophyll a shall not exceed [0.005 mg/l].*
>
> *Fish shall not be rendered unsuitable for human consumption by the presence of contaminants."*

Lake Te Anau and Manapouri are classified as "natural state waters". The water quality standard set for natural state lakes is "*the natural quality of these waters shall not be altered*". Thus comparing against this standard is done by comparing water quality trends over time. No other water quality standard is set for lakes in 'natural state' areas; however for the purpose of comparing state against a standard we have used the highest RWP standards set for lakes in 'mountain areas', i.e. chlorophyll *a* concentrations shall be less than 0.002 mg/l, Secchi depth shall not be less than 10 metres, the concentration of total ammonia shall not exceed 0.32 mg/l.

1.3 Trophic Level Index

New Zealand protocols for monitoring lake trophic levels and assessing trends in trophic state were developed by Burns *et al* (2000). These protocols summarise key water quality variables (total nitrogen, total phosphorus, chlorophyll *a* and Secchi depth) within a Trophic Level Index (TLI). The overall TLI score for a lake is the average of individual TLI scores for each variable. The overall score is categorised into seven trophic states indicating progressively more nutrient enrichment, more algal productivity and reduced water clarity. These are:

Trophic State	**TLI Score**	**Example**
ultra-microtrophic	<1	
microtrophic	1–2	Lake Pukaki, Canterbury
oligotrophic	2–3	Lake Te Anau, Lake Wakatipu
mesotrophic	3–4	Lake Vincent, Southland
eutrophic	4–5	Waituna Lagoon, Southland
supertrophic	5–6	Lake Okaro, Bay of Plenty
hypertrophic	>6	Lake Ellesmere, Canterbury

The monitoring protocols promote reasonably intensive monitoring initially in order to obtain a baseline of lake water quality and to define seasonal changes and lake dynamics. After several years the monitoring intensity is sometimes reduced to focus on tracking water quality changes over the long term. Long term trends are measured using Percent Annual Change (PAC) as an indicator.

1.4 CCME Water Quality Index

Environment Southland is considering using the Canadian Council of Ministers of the Environment (CCME) Water Quality Index to summarise river and lake water quality data and describe it in relation to targets set in the Water Plan. The Index incorporates three elements:

- scope - the number of variables not meeting water quality targets;
- frequency - the number of times these targets are not met; and
- amplitude - the amount by which the targets are not met.

These are combined to produce a single value (between 0 and 100) that describes water quality, where 0 indicates worst water quality and 100 the best water quality. The Index ranks water quality into the following five categories:

Excellent: (CCME WQI Value 95-100) – water quality is protected with a virtual absence of threat or impairment; conditions very close to natural or pristine levels.

Good: (CCME WQI Value 80-94) – water quality is protected with only a minor degree of threat or impairment; conditions rarely depart from natural or desirable levels.

Fair: (CCME WQI Value 65-79) – water quality is usually protected but occasionally threatened or impaired; conditions sometimes depart from natural or desirable levels.

Marginal: (CCME WQI Value 45-64) – water quality is frequently threatened or impaired; conditions often depart from natural or desirable levels.

Poor: (CCME WQI Value 0-44) – water quality is almost always threatened or impaired; conditions usually depart from natural or desirable levels.

The CCME (2001) notes that the CCME WQI should not be applied to small datasets of less than four variables and four sampling visits per year. Furthermore, the CCME WQI should only use site-specific targets (or guidelines) for those variables that are most relevant for the site. The usefulness of the Index relies on realistic objectives and the use of poorly thought out objectives can yield misleading index values.

1.5 LakeSPI

LakeSPI is a management tool that uses Submerged Plant Indicators (SPI) to assess the ecological condition of New Zealand lakes based on key features of macrophyte community structure and composition (Clayton and Edwards 2006(a) (b)). Key features of aquatic plant structure and composition are used to generate the following three LakeSPI indices:

- Native Condition Index – this captures the native character of vegetation in a lake. A higher score means a healthier, more diverse community of native plants growing to greater depths.
- Invasive Condition Index – this captures the invasive character of vegetation in a lake. A higher score means more impact from exotic plants, which is often undesirable.
- LakeSPI Index – this is a synthesis of the Native Condition Index and the Invasive Condition Index and provides an overall indication of lake condition. The higher the score the better the condition of the lake.

The LakeSPI indices in this report are expressed as a percentage of a lake's maximum scoring potential and corresponds to the depth of each lake. The highest possible LakeSPI Index is 100 percent. The classes of ecological condition used for reporting LakeSPI results in this report are:

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

These class boundaries are consistent with those now commonly used for reporting LakeSPI (Mary De Winton, personal communication).

The results from TLI and LakeSPI are complementary in that water quality monitoring emphasises changes in the lake water column, usually in the lake's central basin, while LakeSPI emphasises the littoral zone around the lake margin. LakeSPI includes a measure of lake water clarity implicitly by assessing the maximum depth to which plants grow (which is usually controlled by light – e.g. Vant *et al.* (1986).

1.6 Lake Monitoring

Environment Southland regularly monitors water quality on three lakes: Lake Te Anau, Lake Manapouri and Waituna Lagoon. In addition, spot sampling of water quality has occurred in a number of small coastal lakes (i.e. Lake Vincent, Lake George, Forest Lake and The Reservoir). Sampling of Lake Te Anau and Lake Manapouri occurs at two depths (top and bottom) while there is only a single depth sampled in Waituna Lagoon.

Ecological condition has been assessed by NIWA using LakeSPI for six lakes in Fiordland (Lake Te Anau, Lake Manapouri, Lake Hauroko, Mavora Lake North, Mavora Lake South and Lake Gunn). A description of monitored lakes is provided in Table 1.1 and the location of these lakes is shown in Figure 1.1. The location of SOE monitoring sites on Lake Manapouri and Lake Te Anau is shown in Figure 1.2.

Table 1.1: Description of monitored lakes in Southland

Lake	**Water Plan Classification**	**Maximum Depth (m)**	**Catchment Area (km^2)**	**Lake area (km^2)**	**Dominant land use**
Lake Te Anau	Natural State	417	2998	343	Native
Lake Manapouri	Natural State	444	1428	142	Native
Waituna Lagoon	Coastal Lakes and Wetlands	3.3 (1.6 if open)	210	16.34 (7.21 if open)	Pasture
Lake Hauroko	Natural State	462	554	68	Native
Mavora Lake North	Natural State	77		10.2	Native
Mavora Lake South	Natural State	40		1.6	Native
Lake Gunn	Natural State	60	22	1.7	Native

Sources: Waters of National Significance (WONI) lake classification (DoC); Livingston *et al.* (1986); Waituna Lagoon data from Schallenberg *et al*. (2010); Mavora Lake depth from NZOI 1981.

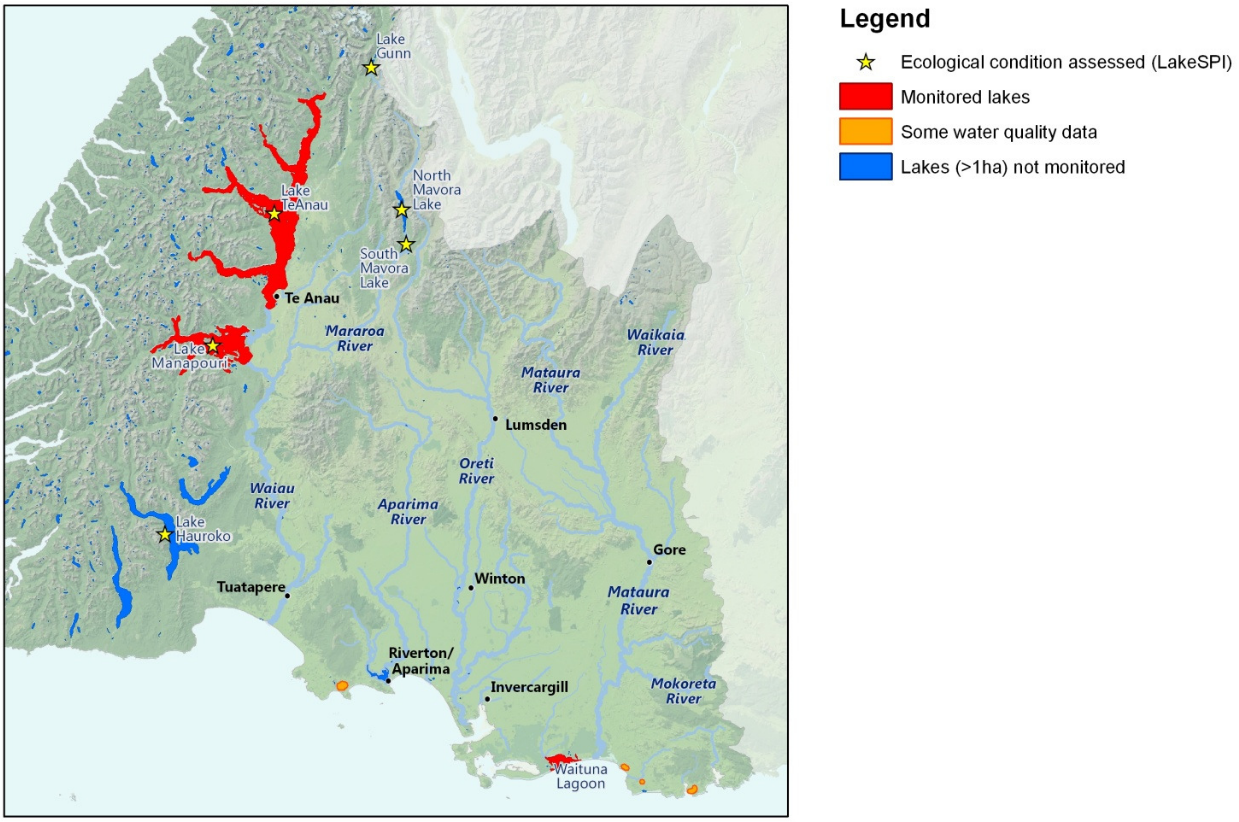

Figure 1.1: Location of lakes in Southland where water quality and/or LakeSPI monitoring has been undertaken.

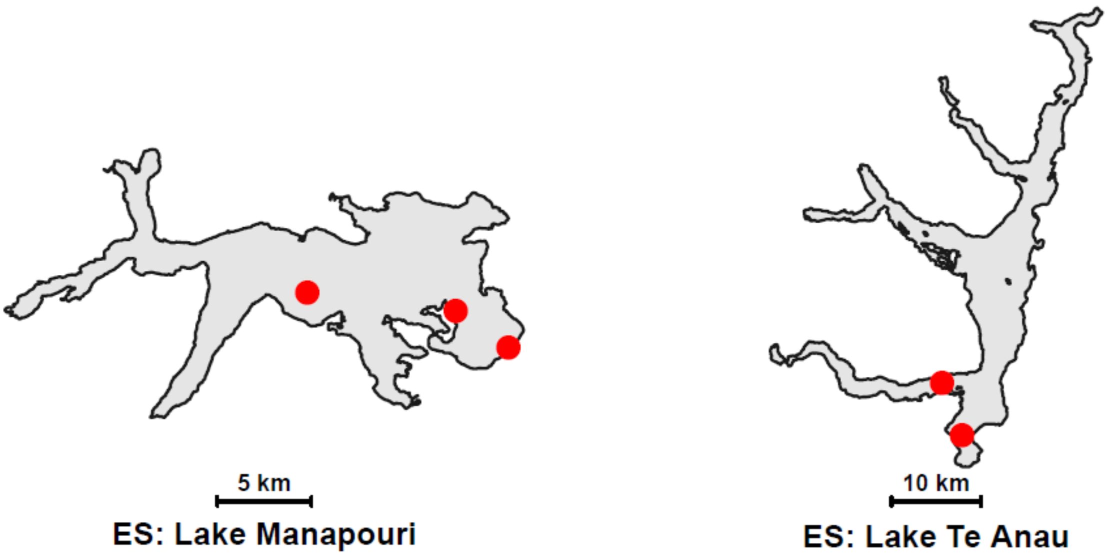

Figure 1.2: Location SOE monitoring sites on Lake Te Anau and Lake Manapouri.

2 Methods

2.1 State of lake water quality

The state of lake water quality was assessed for the period 1 July 2005 to 30 June 2010 using surface water samples. Nutrient concentrations below detection limits were replaced with values equal to half the detection limit. Water quality was assessed for all sites individually and the average for each site was used to summarise the water quality in each lake. The error bars on graphs represent the 10^{th} and 90^{th} percentile values of all samples at all sites on a lake over the time period.

Open and closing Waituna Lagoon to the sea can have a significant influence on its water quality, consequently the water quality in Waituna Lagoon was assessed using both the full dataset and filtering the dataset to only include data from when the lagoon was closed to the sea.

2.1.1 Calculating the TLI

The Trophic Level Index (TLI) (Burns *et al.* 2000) was calculated using the following regression equations:

TLn = -3.61 + 3.01 log (mg TN/m^3)

TLp = 0.218 + 2.92 log(mg TP/m^3)

TLs = 5.10 + 2.6 log(1/SD – 1/40) [1]

TLc = 2.22 + 2.54 log(mg Chla/m^3)

TLI = (TLn + TLp + TLs + TLc)/4

Waituna Lagoon had very little Secchi depth data so the TLI for Waituna Lagoon was calculated as TLI3[2]. Verburg *et al.* (2010) compared TLI3 and TLI4[3] for all monitored NZ lakes and found that TLI3 did not differ significantly from TLI4 (R^2 = 0.98, linear regression TLI4 = 0.99TLI3 + 0.03), which suggests appreciable redundancy between Secchi and TN, TP and chlorophyll *a* data.

2.1.2 Equivalent TLI targets for the Water Plan

The Southland Water Plan has set targets for chlorophyll *a* and Secchi depth but not for TLI. To allow comparisons with the TLI, the chlorophyll *a* targets were converted to an equivalent TLIc using the approach and formula from Burns *et al*. (2000): TLc = 2.22 + 2.54 log(Chl a) [4]. This conversion found that the Water Plan targets for lowland and mountain

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[1] The original formula used in Burns *et al.* (2000) was TLs = 5.10 + 2.27 log(1/SD – 1/40), this was updated to TLs = 5.10 + 2.6 log(1/SD – 1/40) in Burns *et al.* (2005). The original formula was devised from data from brown, humic stained lakes, while the revised formula is more appropriate for clear water lakes.

[2] TLI3 = TLI calculated using TN, TP and chlorophyll *a* data only.

[3] TLI4 =. TLI calculated using TN, TP, chlorophyll *a* and Secchi depth data

[4] This is the same approach as used by Burns *et al.* (2000), i.e. they defined the trophic level index using Chlorophyll *a* data and normalised the other variables against the trophic state index for Chlorophyll *a*.

lakes are equivalent to a TLI target of 4.0 (mesotrophic-eutrophic) and 3.0 (oligotrophic-mesotrophic) respectively.

2.2 Calculating the CCME Water Quality Index

The CCME Water Quality Index (CCME WQI) was calculated for sites on Waituna Lagoon using an automated Excel macro developed by the CCME and modified by Water Resources Management Division of Newfoundland and Labrador (see the web site http://www.env.gov.nl.ca/env/waterres/quality/background/cwqi.html). The equations used in the calculation are provided in Appendix 1 and described in the information sheet by CCME (2001).

The CCME WQI was applied to data for the period the period 1 July 2005 to 30 June 2010. The Water Plan has six variables which were tested: temperature, pH, total ammonia, chlorophyll *a*, percent dissolved oxygen, and Secchi depth. Prior to analysis dissolved oxygen data was converted to percent saturation dissolved oxygen using DO, temperature and electrical conductivity data.

There was too little data to get a reliable estimate of Secchi depth in Waituna Lagoon. However, Secchi depth can be estimated by using a relationship between turbidity and the small amount of Secchi depth data that was available from all sites on the lagoon. The relationship between these variables was $y = -0.11\ x + 1.94$ ($n = 18$, $R^2 = 0.51$). This relationship was used to calculate a synthetic Secchi depth record for Waituna Lagoon to use in the analysis.

Schallenberg *et al*. (2010) found that turbidity peaks in Waituna Lagoon occurred during high wind events. Thus it was assumed that the turbidity in Waituna Lagoon was primarily influenced by resuspension of the bottom sediments by wind and no adjustment was made to the turbidity/Secchi depth data to account for whether the in-flowing streams were above or below median flow.

To simplify the calculations of the CCME WQI for total ammonia variable, a target of 0.9 mg/l was applied to the lagoon. This is equivalent to the ANZECC default guideline with a pH of 8.0. The pH was above 8.0 on 7 (Waituna Lagoon east) to 14 (Waituna Lagoon south) occasions, but on all of these occasions the total ammonia concentration was considerably less than the corresponding ANZECC guideline value.

2.3 Trends in lake water quality

The reliability of water quality trends improves with the length of record assessed, thus water quality trends were assessed for Lake Te Anau, Manapouri and Waituna Lagoon using the full length of record available. This corresponded to the following periods:

- Lake Te Anau July 2000 - June 2010;
- Lake Manapouri Stony Point and Pomona Island: April 2002 - June 2010;
- Lake Manapouri Frasers Beach Sept 2004 - June 2010;

- Waituna Lagoon July 2003 - June 2010.

Trends were assessed using the seasonal Kendall test and the freeware “TimeTrend”. This is a non-parametric test that accounts for seasonality by calculating the Mann-Kendall test on each season separately, and then combining the results. So for monthly "seasons", January data are compared only with January, February with February, etc.

Trend analysis for Lake Te Anau and Lake Manapouri used quarterly “seasons” starting in May because only quarterly samples are available from recent years. Trend analysis for Waituna Lagoon used monthly “seasons”.

The test estimates the magnitude of change using the Sen slope. This is the median annual slope of all possible pairs of values in each season. The Percent Annual Change (PAC) was assessed by dividing Sen slope by the median of the variable and expressing it as a percentage.

A trend test was only considered to be statistically significant if the p-value was less than 0.05 (after Burns *et al.* 2001), and only considered to be meaningful if it had an annual trend of more than 0.5% of the median value. The lower the p-value the more likely it is that the lake has changed with time, and the smaller the rate of change the less substantial is the trend.

Covariate adjustment

The water quality in Waituna Lagoon is influenced by whether the lagoon is open or closed, to account for this an additional trend analysis was done using TimeTrend software to adjust the data for salinity (expressed as electrical conductivity (EC)). The adjustment developed a General Additive Model (Gam) curve (3 degrees of freedom) relationship between the variable and EC and then adjusted each variable according to the value of the curve. The EC adjustment was only used for variables with the relationship covariate with EC explained a more than 20% of the variation for the variable, i.e. for total nitrogen (TN) and Trophic Level Index (TLI).

Total phosphorus (TP) was positively correlated with turbidity in Waituna Lagoon, such that turbidity explained 22% to 52% of the variance depending on the site[5]. Thus TP was adjusted for turbidity using a Gam curve relationship.

In addition to adjustment using EC and turbidity as a covariate, the data was analysed after filtering to include only those values measured when the lagoon was closed.

[5] This was probably due to wind mobilisation of bottom sediments, this is likely to be less when the lagoon is closed due to deeper water.

3 Lake water quality state

3.1 Summary water quality

Median water quality results for surface samples from Southland lake monitoring sites on Lake Te Anau, Lake Manapouri and Waituna Lagoon are shown in Table 3.1 (summary results for all sites including bottom water sites are shown in Appendix 2). The percent of times that selected water quality variables exceeded Water Plan standards and the average magnitude of these exceedances is shown in Table 3.2.

Figures 3.1, 3.2 and 3.3 compares the results of Southland lakes with the median value from all New Zealand lakes and other selected lakes reported in Verburg *et al*. (2010). Figure 3.1 shows that Lake Te Anau and Lake Manapouri are oligotrophic. Chlorophyll *a* data alone suggests that the lakes are microtrophic and it is likely that the large number of non-detect data (Table 3.3) is artificially lifting the measured trophic state. Using TLIc along it is estimated that a more accurate TLI score for Te Anau and Manapouri would be between 1.7 and 1.9. Nevertheless, the data shows that both lakes are in the top 10% of lakes monitored in New Zealand, with and similar water quality to other large lakes like Lake Wakatipu and Lake Taupo (Verburg *et al*. 2010).

In contrast, Waituna Lagoon is eutrophic and exceeds the TLI target for coastal lakes derived from the chlorophyll *a* standard in the Water Plan. Water quality is slightly worse when the lagoon is closed.

Median chlorophyll *a* concentrations (see Figure 3.2) in Lakes Te Anau, Manapouri and Waituna Lagoon are within standards set by the Water Plan for mountain areas and lowland coastal lakes respectively. However, the error bars show that there are times when the standards are breached.

It is interesting to note the number of times Water Plan targets are exceeded for Lake Te Anau and Lake Manapouri considering that these are relatively pristine lakes in a natural state (see Table 3.2). The exceedances might be caused by pressures, but may also reflect the application of the strict Water Plan targets. For example, the Water Plan targets for total ammonia and chlorophyll *a* are applied as maximums that individual samples shall not exceed, this is creates a stricter target compared to equivalent values referred to in the ANZECC guidelines which are applied as average values[6].

Figure 3.3 shows that the water clarity (as indicated by Secchi depth) of Lake Te Anau and Lake Manapouri is high, and about four times better than the median for New Zealand lakes (Verburg *et al* 2010). The lower water clarity in Lake Te Anau and Manapouri compared to other large lakes such as Lake Wakatipu or Lake Taupo probably reflects the slight humic staining in the water from the predominantly native bush catchment.

There was too little Secchi depth data to get a reliable estimate for Waituna Lagoon, thus a relationship between turbidity and Secchi depth ($y = -0.11\ x + 1.91$ ($R^2 = 0.53$)) was used to calculate a synthetic Secchi depth record. This method estimated the median Secchi depth

[6] The ANZECC guideline does not set specific trigger values for chlorophyll *a* in NZ but does discuss broad relationships between chl *a* and trophic status of waterbodies in Table. 8.2.1.

to be 1.1 m for Waituna Lagoon east and 1.2 m at all other sites. This breaches the standard set by the Water Plan for lowland coastal lakes.

Median chlorophyll *a* concentrations in Waituna Lagoon are within the Water Plan standard. An examination of individual components of the TLI in Waituna Lagoon shows that concentration of chlorophyll *a* is relatively low compared nutrient concentrations, i.e. the TLI components for all sites was TLI n = 5.1, TLI p = 4.8 and TLI c = 3.1. This suggests that some factors (e.g. flushing, competition for available nutrient) may be reducing the growth of phytoplankton in the lagoon.

Table 3.1 also shows summary data for spot samples from Forest Lake, Lake George, Lake Vincent and the Reservoir. The data for these lakes should be viewed with caution because of the limited number of samples, however they do indicate that these small coastal lakes are in a eutropic to supertrophic condition, with high concentrations of nutrients.

There were a large number of nutrient and suspended sediment samples from Lake Te Anau and Lake Manapouri that were below detection limit. The percentage of data recorded as below detection limit in surface water samples is shown in Table 3.3. The large number of these non-detect samples present a problem for accurately assessing the state of the lake and seriously limits the ability of the monitoring to detect water quality trends[7].

Good progress has been made by Environment Southland in improving detection limits in recent years but further improvements could be made by modifying the analytical methods used. In particular, TSS and VSS should be analysed using the low level method (requiring two litres of sample) to give a detection limit of 0.5 g/m^3 compared to 2.5 g/m^3.

TP is currently analysed with a detection limit of 0.004 g/m^3 but some laboratories (e.g. NIWA) can achieve detection limits of 0.002 g/m^3 or less. TN is currently analysed using the TKN method which has a detection limit of about 0.1 g/m^3, different methods can achieve a detection limit of 0.01-0.02 g/m^3. Chlorophyll *a* is currently being analysed with a detection limit of 0.003 g/m^3 but has previously had a detection limit of 0.0001 g/m^3.

[7] The same problem was found for bottom water samples.

Table 3.1: Median water qualtiy for Southland lake monitoring sites July 2005 to June 2010.

Site	n	Water Temp (oC)	pH	EC (uS/cm)	DO (mg/L)	TN (mg/l)	NNN (mg/l)	NH4-N (mg/l)	TP (mg/l)	DRP (mg/l)	Chl a (mg/l)	Turbidity (NTU)	Secchi (m)	VSS (mg/l)	TSS (mg/l)	TLI4	TLI3
Manapouri at Frazers Beach Top	37	11.0	7.1	31	10.5	<0.11	0.032	<0.01	<0.01	<0.004	0.0015	0.3	11.2	<2.5	<2.5	2.0	
Manapouri at Stony Point Top	35	10.9	7.2	31	10.3	<0.11	0.034	<0.01	<0.01	<0.004	0.0015	0.3	11.7	<2.5	<2.5	2.0	
Manapouri at Pomona Island Top	36	10.5	7.1	30	10.2	0.084	0.033	<0.01	<0.01	<0.004	0.0015	0.4	11.9	<2.5	<2.5	2.0	
Te Anau Blue Gum Point Top	37	9.8	7.2	31	10.2	<0.11	0.034	<0.01	<0.01	<0.004	0.0011	0.4	11.6	<2.5	<2.5	2.0	
Te Anau South Fiord Top	38	10.1	7.2	31	10.5	0.090	0.036	<0.01	<0.01	<0.004	0.0009	0.3	12.1	<1.2	<2.5	1.9	
Waituna Lagoon east	45	12.7	7.8	5600	9.8	0.750	0.022	0.014	0.036	0.002	0.0021	5.8			4.3		4.3
Waituna Lagoon south	54	12.2	7.8	7870	9.3	0.745	0.054	0.015	0.035	0.005	0.0022	5.8			4.5		4.4
Waituna Lagoon centre	49	11.9	7.7	6780	9.4	0.760	0.040	0.014	0.041	0.005	0.0032	5.7			5.2		4.6
Waituna Lagoon west	54	11.9	7.8	7250	9.1	0.800	0.129	0.014	0.040	0.005	0.0024	7.0			7.0		4.5
Waituna Lagoon east closed	37	12.9	7.8	4300	10.1	0.780	0.018	0.012	0.038	0.002	0.0020	6.0			4.2		4.3
Waituna Lagoon south closed	39	12.8	7.8	4240	10.0	0.800	0.034	0.014	0.036	0.002	0.0022	5.3			4.1		4.6
Waituna Lagoon centre closed	35	12.7	7.6	3860	10.2	0.930	0.103	0.013	0.042	0.005	0.0037	6.3			5.1		4.7
Waituna Lagoon west closed	39	12.5	7.7	4110	9.3	1.000	0.118	0.012	0.040	0.005	0.0024	6.7			6.4		4.7
Forest Lake	1		4.9	316		2.000	0.016	0.065	0.710	0.480							
Lake George	1	13.2	7.7	192	9.9	1.100	0.005	0.010	0.074	0.008		30.0					
Lake Vincent East top	2	12.8	8.3	287	11.7	0.780	0.018	0.005	0.030	0.004	0.0081	3.0	1.5				4.7
Lake Vincent West top	2	12.5	7.8	292	10.9	0.625	0.005	0.005	0.124	0.005		2.5	1.8				5.0
Reservoir South	3	10.1	7.7		11.1	0.670	0.005	0.005	0.040	0.003	0.0076	8.2	0.8				5.0
Resevoir North	3	10.0	7.6	275	10.6	0.680	0.005	0.005	0.040	0.014	0.0051	9.2	0.8				4.9

Note:
Data for Forest Lake, Lake George, Lake Vincent and the Reservoir should be treated with caution as it is based on few spot samples in 2000 & 2007.
There were insuffiecent measurements to provide reliable Secchi depth data for Waituna Lagoon.
TSS was based on a limited dataset of 17 samples since 2008.
Bottom water samples had similar values to top samples for all parameters except TN and NNN.
Bottom water TN samples from Lake Manapouri at Pomona Island and Stoney Point were respectively 50% and 69% higher than top water samples.
TLI4 = TLI using TN, TP, Chl a and Secchi depth; TLI4 = TLI using TN, TP and Chl a.

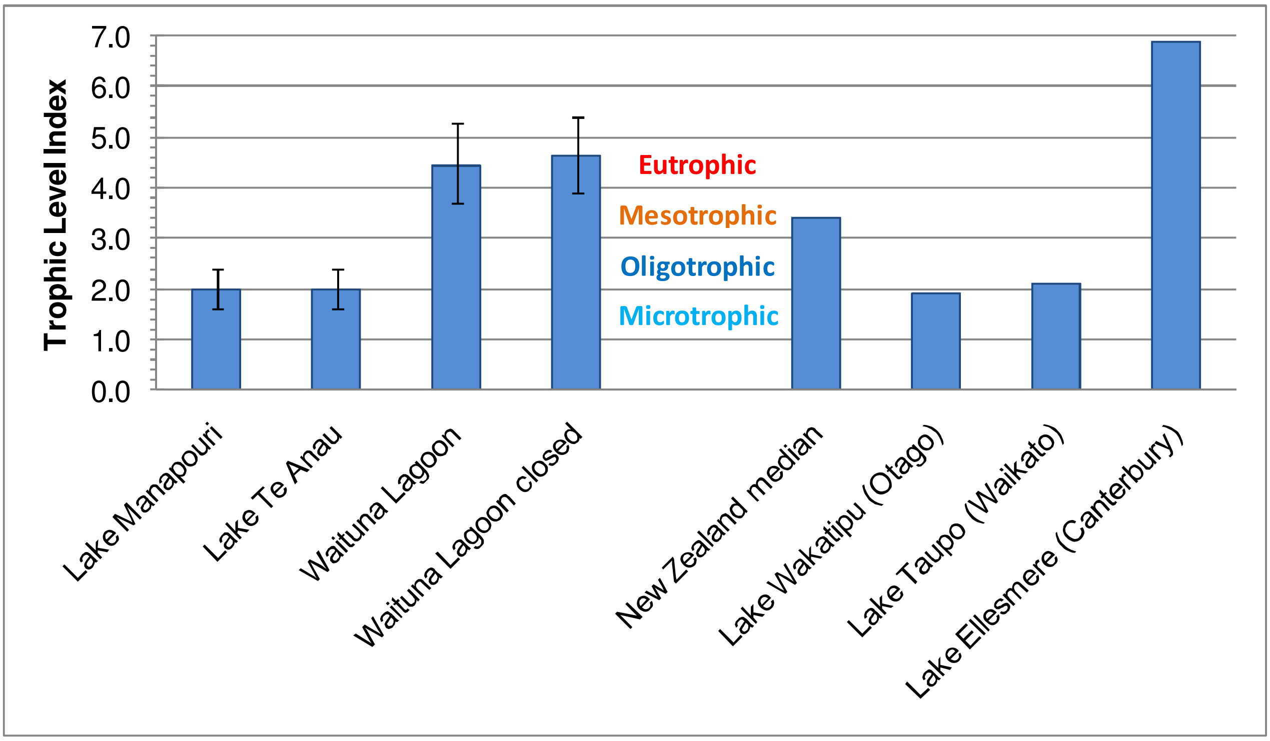

Figure 3.1: Median Trophic Level Index of Southland lakes. Error bars show 10th and 90th percentile values.

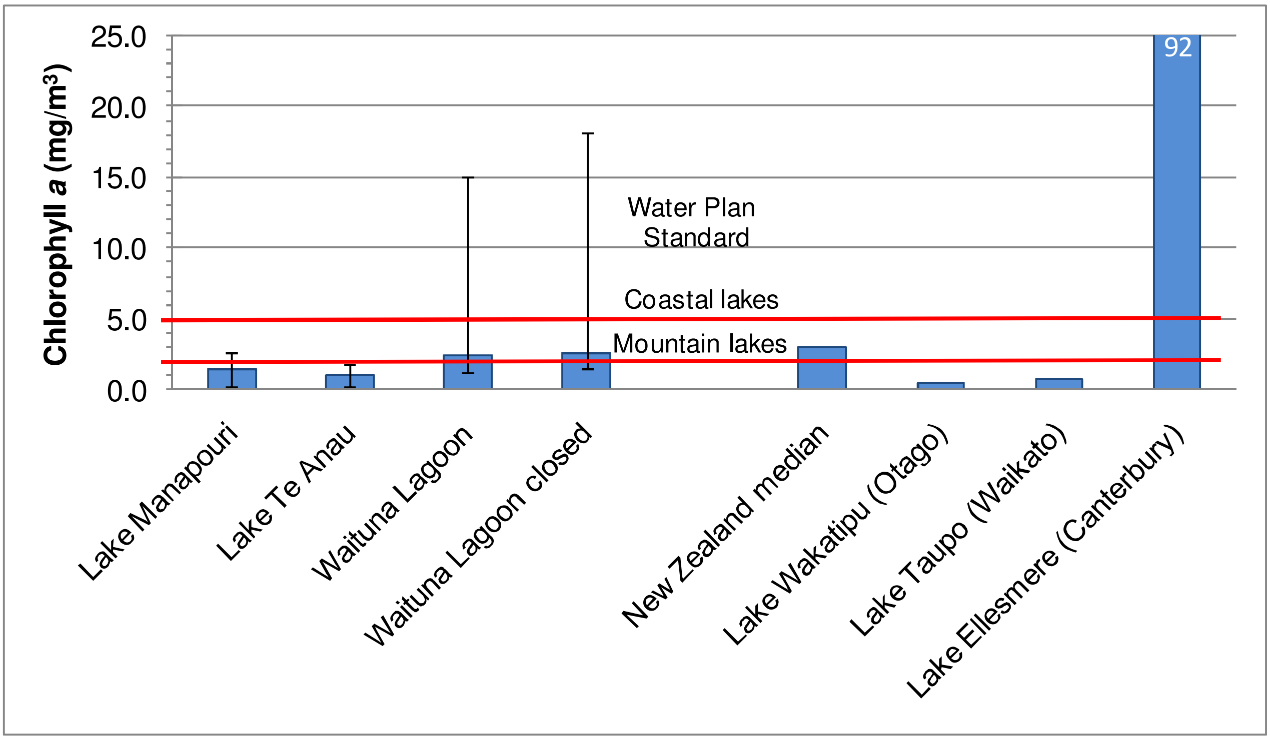

Figure 3.2: Median chlorophyll *a* concentration in Southland lakes. Error bars show 10th and 90th percentile values. The red lines show the Water Plan standard for Coastal Lakes and Mountain lakes.

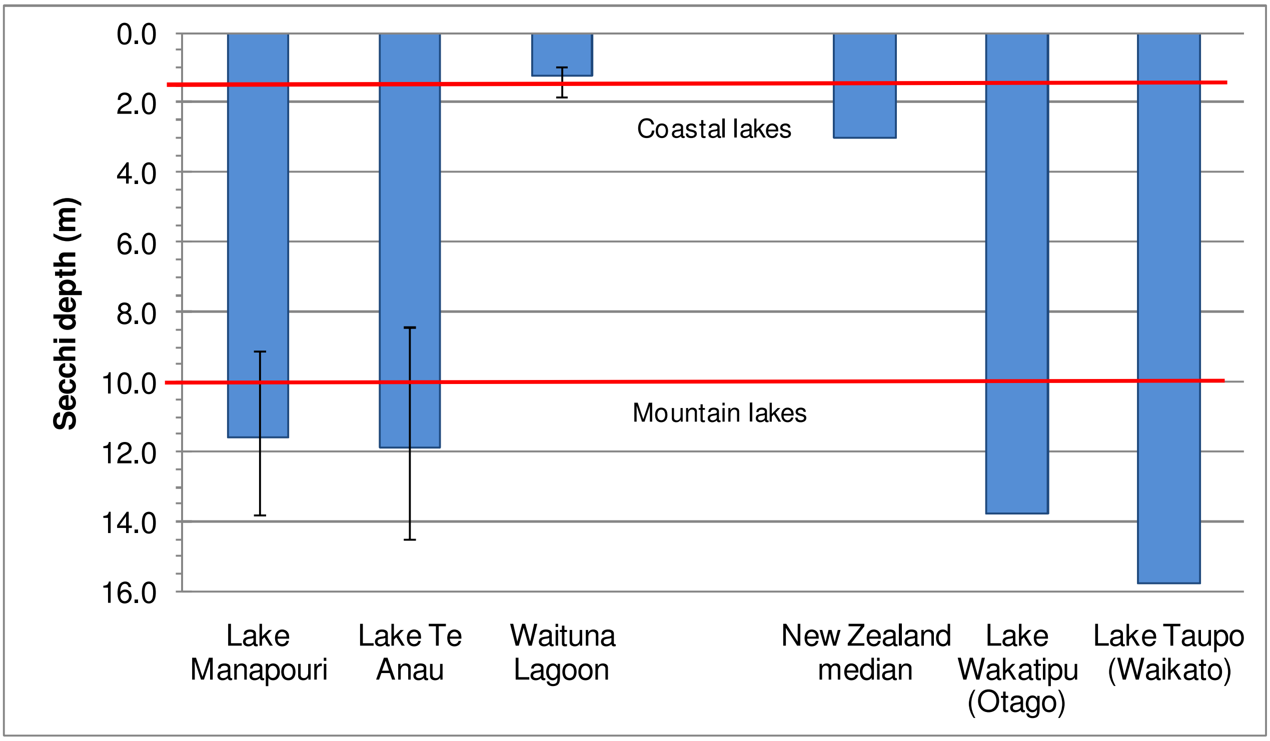

Figure 3.3: Median Secchi depth of Southland lakes. Error bars show 10th and 90th percentile values. The red lines show the Water Plan standard for Coastal Lakes and Mountain lakes.

Table 3.2: Frequency and magnitude of exceedance of Water Plan standards.

	Frequency target exceeded (% exceeding target)			Magnitude of excedance (average of values above target)		
Variable	**Chl a**	**Secchi**	**TLI**	**Chl a (mg/l)**	**Secchi (m)**	**TLI**
Manapouri at Frazers beach top	9.3%	19%	2.1%	0.003	8.8	3.8
Manapouri at Pomona Is top	6.3%	15%	2.9%	0.004	8.9	3.1
Manapouri at Stony point top	8.1%	34%	0.0%	0.003	8.4	0.0
Te Anau Blue Gum Point Top	3.5%	28%	1.1%	0.004	8.1	3.0
Te Anau South Fiord Top	2.3%	18%	2.2%	0.002	8.1	3.4
Waituna Lagoon centre	36%	2.8%	68%	0.012	1.0	4.8
Waituna Lagoon east	31%	4.9%	75%	0.010	1.1	4.6
Waituna Lagoon south	27%	1.4%	67%	0.016	1.0	4.7
Waituna Lagoon west	38%	1.4%	78%	0.019	1.0	4.8

Note: The total ammonia target was not exceeded at any lake monitoring site.
Targets applied to Manapouri and Te Anau were respectively 0.002 mg/l, 10m and 3 for Chl a, Secchi depth and TLI.
Targets applied to Waituna Lagoon were respectively 0.005 mg/l, 1.5 and 4 for for Chl a, Secchi depth and TLI.

Table 3.3: Percentage of data recorded as below detection limit for Lake Te Anau and Lake Manapouri

Site	TN	NNN	NH4-N	TP	DRP	Chl a	TSS
Manapouri at Frazers beach Top	65	0	62	89	86	30	97
Manapouri at Pomona Island Top	64	0	75	92	86	40	97
Manapouri at Stony point Top	57	3	77	91	89	40	97
Te Anau Blue Gum Point Top	57	0	57	78	70	40	86
Te Anau South Fiord Top	48	0	68	87	92	50	97

3.2 Dissolved oxygen

Depth profiles of dissolved oxygen and temperature have been regularly measured at sites in Lakes Te Anau and Lake Manapouri. This monitoring is important because when a lake stratifies the bottom waters can consume oxygen. The rate of oxygen consumption depends of the productivity (trophic state) of the lake. In eutrophic lakes the oxygen concentration in bottom water can get very low, adversely affecting aquatic life and increasing nutrient release from lake sediment. This creates a positive feedback loop whereby eutrophication promotes anoxic bottom waters, which release nutrients and cause increased eutrophication.

Table 3.4 shows summary data from an analysis of lake profiles from January 2006 to December 2010 (~18 profiles per site). This shows that there is a reduction of dissolved oxygen in the hypolimnion could at times be stressing fish (7-day average DO should be greater than 6.5 to protect adult fish), but the bottom waters never become anoxic (DO < 1 mg/l), and so does not increase the rate of internal nutrient cycling from the bottom sediments.

A typical dissolved oxygen-temperature profile is shown in Figure 3.4. This shows a thermocline at about 16-20 metres in January lowering to about 40 m in February. January DO concentrations were relatively stable below the thermocline. The deep thermocline explains why summer stratification has not been detected at Frasers Beach site, which has a maximum depth of about 20m.

It should be noted that at the deep water sites of Manapouri at Pomona Island and Te Anau at South Fiord the depth profiles have not been recorded to the bottom of the lake, and it is possible that dissolved oxygen continues to decline with depth and lower dissolved oxygen concentrations occur in deeper water.

Table 3.4: Summary data from dissolved oxygen-temperature depth profiles (2006-2010)

Site	% time stratified	Average Depth (m)	Bottom DO (average when stratified)	Bottom DO (minimum when stratified)
Manapouri at Pomona Island	44%	103	8.8	6.5
Manapouri at Stony Point	41%	72	9.2	6.6
Manapouri at Frasers Beach	0%	20	-	-
Te Anau at South Fiord	33%	102	9.5	8.4
Te Anau at Blue Gum Point	11%	55	9.7	9.5

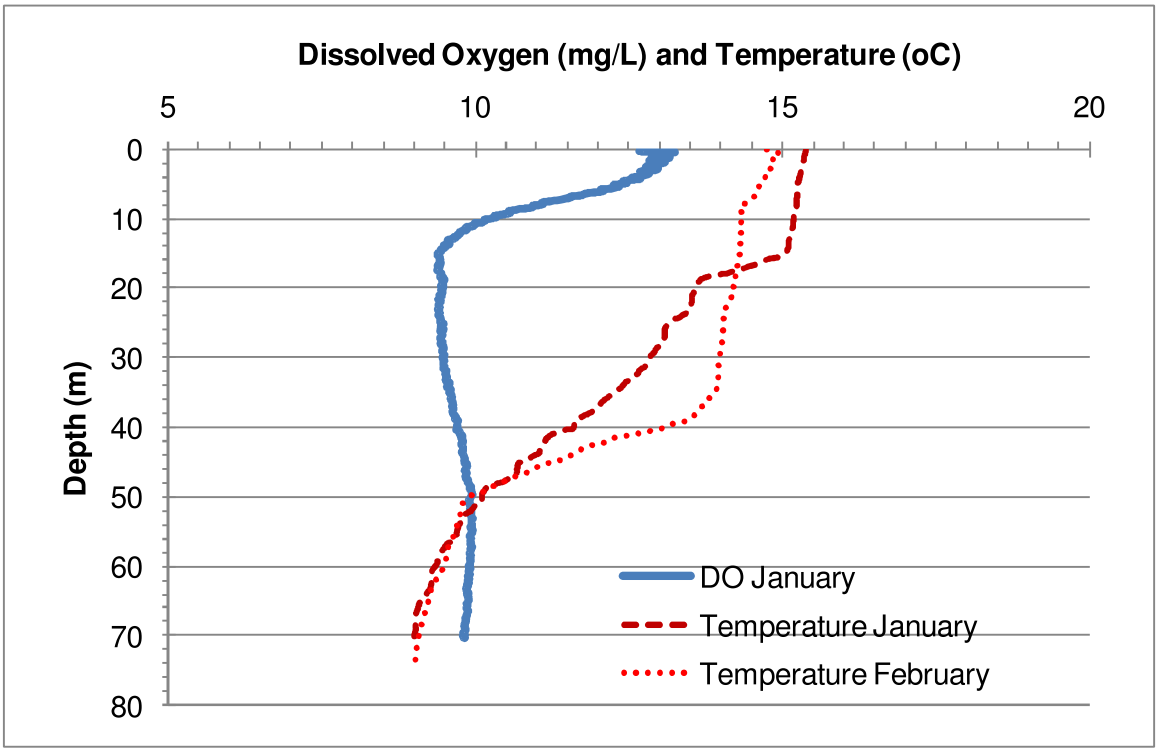

Figure 3.4: Dissolved oxygen – temperature – depth profile at Lake Manapouri Stony Point January 2009 and February 2009.

3.3 Water quality assessed by the CCME Water Quality Index

The CCME Water Quality Index categorised the Waituna Lagoon as "Fair" – "Marginal" for the period 2005-2010. Most sites on the Waituna Lagoon were classified as "Fair" (i.e.

conditions sometimes depart from desirable levels), but the west site was "Marginal. A summary of the CCME WQI results for each site is shown in Table 3.5.

The worst water quality at the west site was due to a single failure of pH against the standard (pH of 6.4 in August 2008) and the greater magnitude by which variables failed against the Water Plan standards. If the pH failure is ignored (or the Water Plan standard relaxed to be 6.4-8.5 instead of 6.5-8.5) than the west sites would also be classified as "Fair" with a CCME WQI score of 65.

The variables of temperature and total ammonia always met the Standards at all sites, but all sites had failures for Chlorophyll *a*, Secchi depth, and %DO. The variable with the most failed tests was Secchi depth (for all sites), the variables with the greatest excursion from the standard (normalised sum of excursion) were Secchi depth at the east site and Chlorophyll *a* at all other sites.

Consideration could be given as to whether the pH standard in the Water Plan is appropriate for the Waituna Lagoon considering that a significant proportion of the catchment in the west is a peat wetland with naturally acid soils.

Table 3.5: CCME WQI results for Waituna Lagoon (July 2005 – June 2010)

Site	CCME WQI Category	CCME WQI socre	Scope (F1)	Frequency (F2)	Amplitude (F3)
Waituna Lagoon east	Fair	68	50%	21%	12
Waituna Lagoon south	Fair	68	50%	19%	17
Waituna Lagoon centre	Fair	67	50%	22%	16
Waituna Lagoon west	Marginal	56	67%	23%	27
Waituna Lagoon (all sites)	*Marginal*	*58*	*67%*	*22%*	*19*

3.4 LakeSPI results

NIWA has used LakeSPI to assess the ecological condition of six lakes in Southland as part of a FRST research project. The data used was collected between 2001 and 2007 and all lakes assessed had catchments dominated by native bush.

All lakes assessed in Southland had 'high' LakeSPI scores (i.e. 50%-75%) (see Table 3.6). This puts them in the top one third of NZ lakes, and the top third of NZ lakes in native bush catchment. Verburg *et al*. (2010) found 33% of NZ lakes with LakeSPI scores of 'high' or 'excellent'.

The lakes with the highest ecological condition (i.e. Lake Hauroko, and the Mavora Lakes) had the smallest proportion of invasive plants and the highest proportion of native plants.

Table 3.6: Ecological condition of Southland lakes using LakeSPI

Site	**% LakeSPI**	**% Native**	**% Invasive**	**Plant Depth Score**
Lake Hauroko	70.3	54.8	5.8	4.3
Mavora Lake North	70	71.7	27.8	7
Mavora Lake South	69	73.3	31.5	7
Lake Te Anau	56.7	26.7	62	5
Lake Gunn	53	50	40.7	5
Lake Manapouri	50.7	53.9	48.1	4.3

3.5 Effect of Waituna Lagoon opening

The water quality in Waituna Lagoon is strongly influenced by whether or not the lagoon is open or closed to the sea. When it is open electrical conductivity is about 42,000 uS/cm and when closed it is about 4,100 uS/cm. Since July 2005 the lagoon has been typically closed for about 190 days per year (median value).

An equivalence test between the open and closed state for the variables TN, TP, Chlorophyll *a*, TLI, turbidity and EC found that there was a statistically significant difference ($p<0.05$) at all sites. In most cases the p-value was less than 1 percent.

Opening and closing of the lagoon made most difference to EC, TN, NNN, chlorophyll *a* and TLI and less difference to TP, DRP and turbidity. This is demonstrated in Figures 3.5, 3.6 and 3.7 which shows the change in TLI3, TN and chlorophyll *a* concentrations with electrical conductivity from sea water influence.

Increased hydraulic flushing of a lake can in some cases significantly reduce phytoplankton biomass by flushing cells from the water column when they are in a phase of rapid growth as a result of favourable environmental conditions (e.g., light, nutrients). A hydraulic residence time of less than c. 20 days is required to cause sufficient loss rates of phytoplankton cells for flushing can effectively control biomass. Waituna Lagoon has a hydraulic residence time of 14.5 days based on freshwater inflows (Schallenberg *et al.* 2010), consequently, when the lagoon is open there is less likelihood of a phytoplankton bloom. Figure 3.7 shows that this appears to be the case in Waituna Lagoon, with chlorophyll *a* concentrations mostly restricted to less than 0.01 mg/l when the lagoon is open (i.e. high EC levels).

Schallenberg *et al.* (2010) also found that sea water exchange reduced chlorophyll *a* (and DIN) levels in Waituna Lagoon, but the non-linear relationships suggested complex dilution dynamics. Reducing chlorophyll *a* concentrations may be related not just to seawater dilution but also to flushing.

There is very weak seasonality to chlorophyll *a* concentration in Waituna Lagoon, with peaks mostly restricted to late summer (March – May) and spring (September-October).

Opening Waituna Lagoon to the sea does result in an improvement in water quality however, Schallenberg *et al*. (2010) noted that increasing the frequency of opening could negatively affect fringing wetland vegetation, macrophyte communities, and other biota sensitive to high salinities. We do not fully understand the ideal opening regime for *Ruppia* sp. in Waituna Lagoon and care is needed to ensure that any change in the opening regime to improve water quality does not adversely affect germination of *Ruppia* sp. in the lagoon.

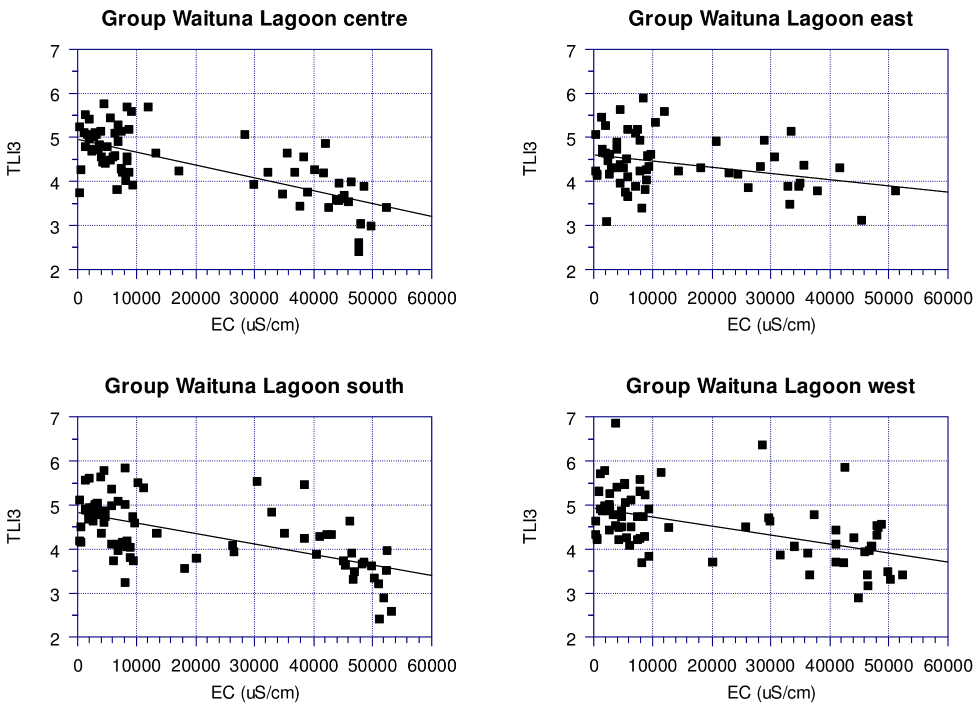

Figure 3.5: Effect of electrical conductivity from seawater influence on TLI score in Waituna Lagoon.

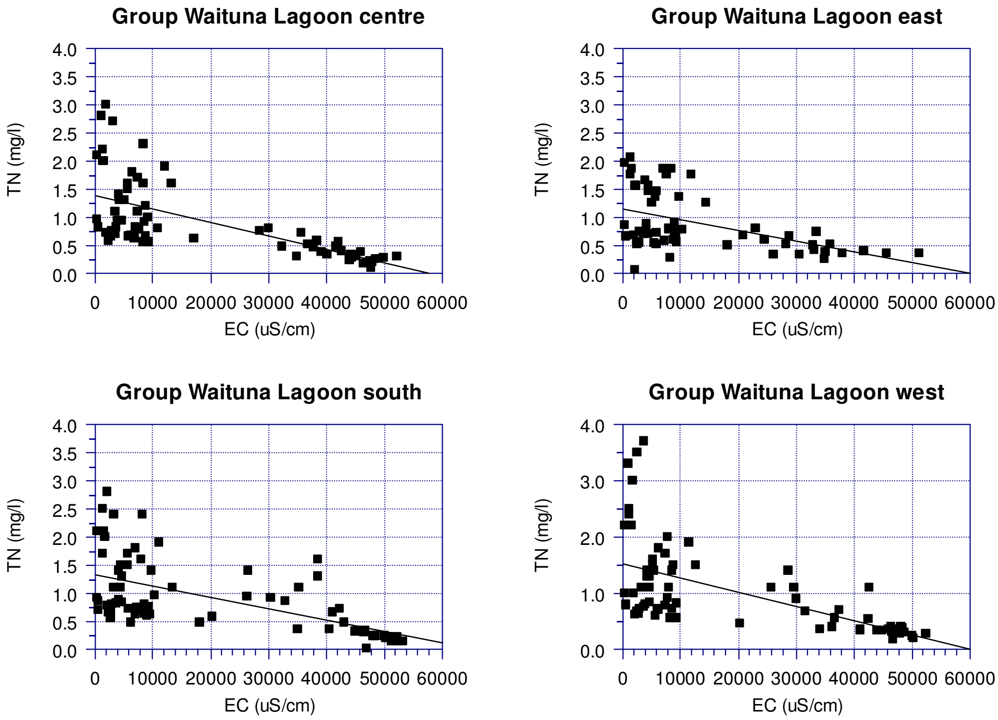

Figure 3.6: Effect of electrical conductivity from seawater influence on TN in Waituna Lagoon

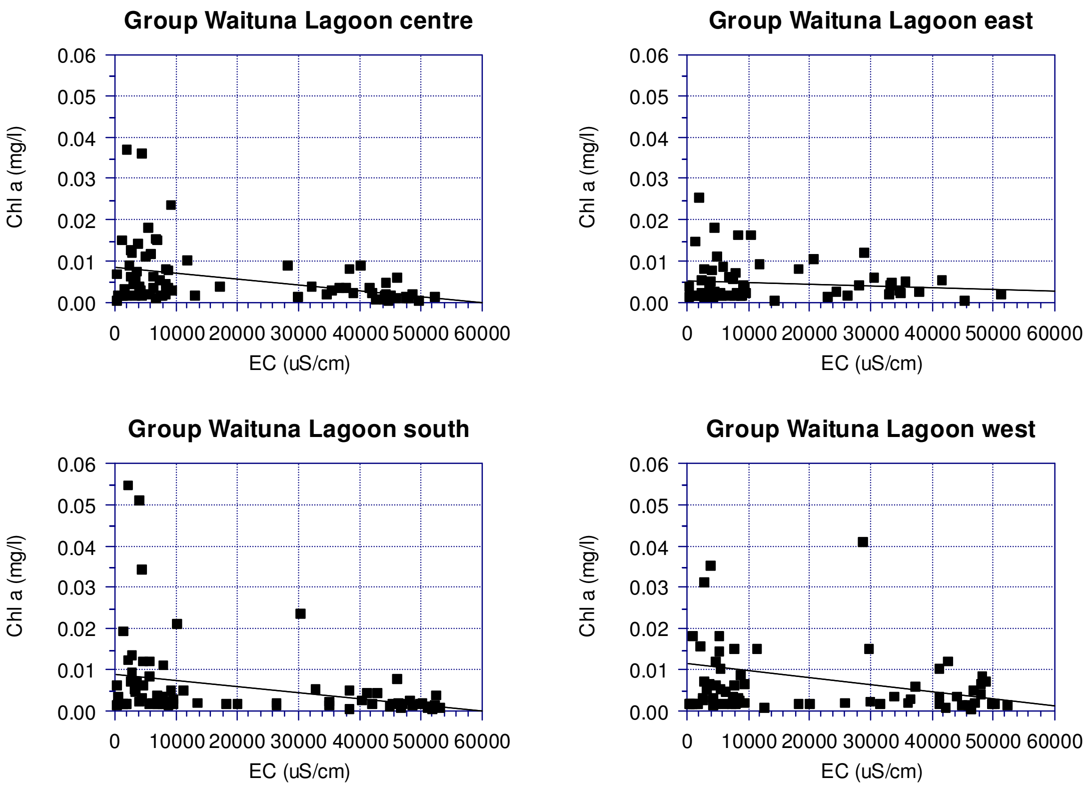

Figure 3.7: Effect of electrical conductivity from seawater influence on chlorophyll *a* concentrations in Waituna Lagoon.

4 Lake water quality trends

4.1 Summary of results Lake Manapouri

Summary results of water quality trend analysis are shown in Table 4.1.

In Lake Manapouri, trends were observed for two variables: a decline in Secchi depth at Frazers Beach since 2004 and a decline in turbidity at Pomona Island Bottom water site. When the data from Stony Point, Pomona Island, and Lake Te Anau sites are analysed since July 2004 the same significant decline in Secchi depth is apparent.

Changes in Secchi depth over time are illustrated in Figure 4.1 and Figure 4.2 for Lake Manapouri at Frazers Beach and Stony Point. Figure 4.1 clearly shows a deterioration in Secchi depth since 2005, but the longer term dataset (since 2002) from both other sites (e.g. Stony Point in Figure 4.2) suggests that the deterioration may be part of a cyclic pattern. Some low Secchi depth readings (<5 m) were also measured at sites in Lake Te Anau in 2009 and 2010, these did not form part of a statistically significant trend in Te Anau but may indicate a common factor affecting Secchi depth measurements.

The reasons for this deteriorating trend should be further investigated, including whether it is related to water from the Mararoa River water back flowing up into the lake, land activities in the catchment, changes in rainfall patterns influencing humic staining in the lake or a systematic error due to a change in measurement method.

The improvement in turbidity at some sites in Lake Manapouri Lake Te Anau is probably an artefact of changes in laboratory detection limits. While the dataset does not include any 'less than' values it is obvious from Figure 4.3 that most of the values were measured to a lower limit and that this changed in 2006. The dataset has strong serial correlation and when this is taken into account no statistically significant trend was found.

An apparent decreasing trend was also observed in Lake Manapouri for total phosphorus as illustrated in Figure 4.4. However this was clearly driven by a lowering of the detection limit in July 2008 when the laboratory used for analysis was changed. Furthermore trend analysis is not reliable when there is a large number of values less than the detection limit.

Table 4.1: Summary of water quality trends in Southland lakes. A shaded cell indicates a significant trend was detected, values without shading indicate weak significance (0.05<*p*-value <0.1), "ns" = not significant.

Site	TLI PAC	TLI p-value	TN PAC	TN p-value	TP PAC	TP p-value	Chl a PAC	Chl a p-value	Secchi PAC	Secchi p-value	Turbidity PAC	Turbidity p-value
Manapouri at Frazers Beach Top		ns		ns		*		ns	-5.5%	0.04		ns
Manapouri at Frazers beach bottom				ns		*						ns
Manapouri at Stony Point Top		ns		ns		*		ns		ns		ns
Manapouri at Stony Point bottom				ns		*						ns
Manapouri at Pomona Island Top		ns		ns		*		ns	*-1.7%*	*0.1*		ns
Manapouri at Pomona Is Bottom				ns	0.0%	*					-6.3%	0.03
Te Anau Blue Gum Point Top		ns	-6.3%	0.03	0.0%	*		ns		ns		ns
Te Anau Blue Gum Point bottom			*-4.7%*	*0.06*		ns						ns
Te Anau South Fiord Top	*-2.0%*	*0.02*	-7.1%	<0.01	0.0%	*		ns		ns	-6.3%	0.01
Te Anau South Fiord bottom		ns	*-4.4%*	*0.09*	0.0%	*					-8.3%	0.04
Waituna Lagoon east		ns	6.7%	0.05		ns		ns				ns
Waituna Lagoon south		ns	11.5%	0.003	*6.7%*	*0.1*		ns				ns
Waituna Lagoon centre	2.4%	0.04	12.7%	<0.001	10.1%	0.01		ns				ns
Waituna Lagoon west			12.7%	0.001		ns		ns				ns
Waituna Lagoon east closed		ns		ns		ns		ns				ns
Waituna Lagoon south closed	*-0.3%*	*0.07*		ns		ns	-12.5%	0.03				ns
Waituna Lagoon centre closed		ns	*5.4%*	*0.09*		ns		ns				ns
Waituna Lagoon west closed		ns		ns		ns	-15.2%	0.04				ns

Note:
Period Te Anau July 2000 - June 2010; Manapouri April 2002 - 2010, Manpouri Frasers Beach Sept 2004-2010; Waituna Lagoon July 2003-2010.
There were no significant trends when Waituna Lagoon TLI and TN data was adjusted for EC as a covariate.
* Statistically significant decreasing trends were detected for TP at all Lake Manapouri site,
however these are not reliable due to the large number of non-detects and changes in the detection limit.
TLI trend for Te Anau South Fiord is unreliable due to a halving in TLc with change in detection limit since min 2008.
Adjusting Waituna Lagoon TP data for turbidity identified an increasing trend at Centre and West sites.

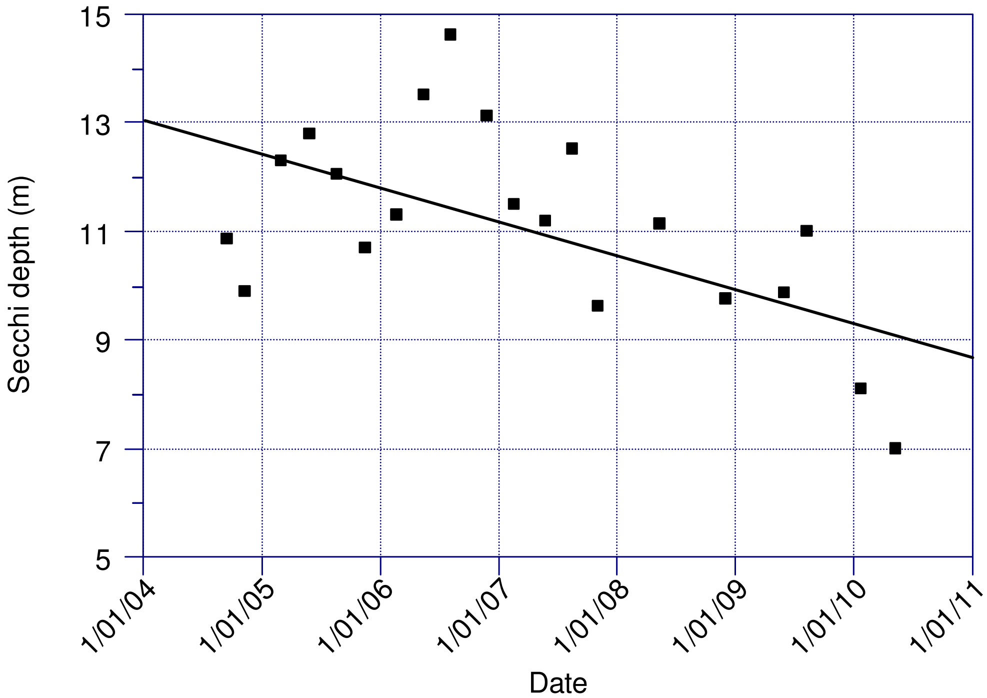

Figure 4.1: Secchi depth (m) in Lake Manapouri at Frasers Beach. A significant deterioration since 2004 (PAC=-5.5%, p-value=0.04).

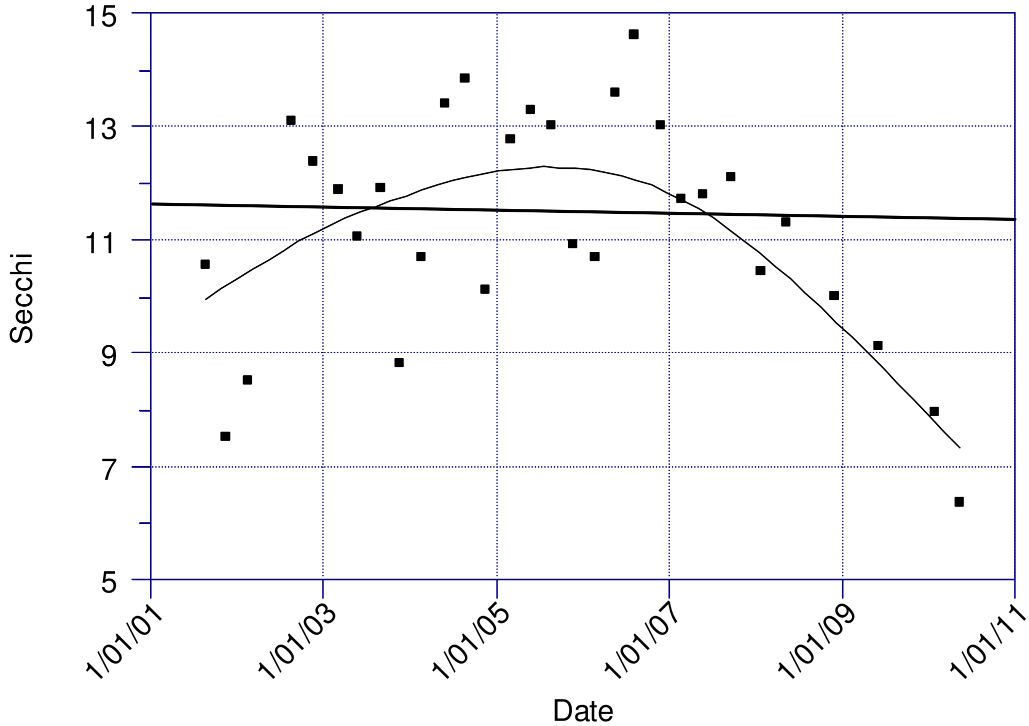

Figure 4.2: Secchi depth (m) in Lake Manapouri at Stony Point. No significant trend since 2002, but a significant short term trend since about 2005.

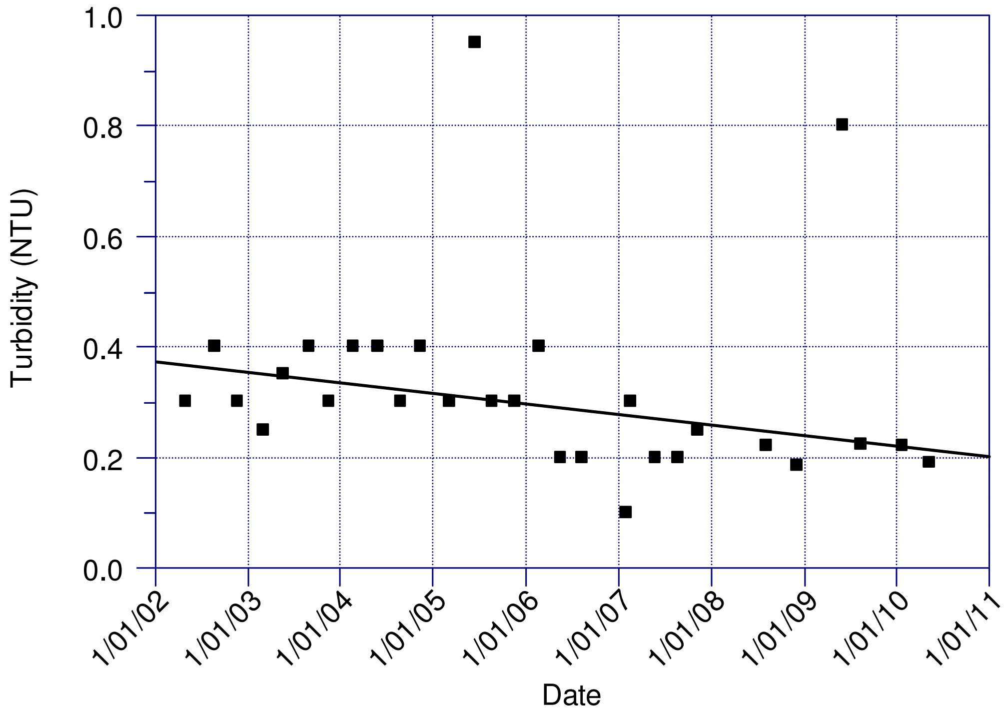

Figure 4.3: Apparent trend in turbidity in Lake Manapouri at Pomona Island bottom water. (PAC=-6.3, p-value =0.03).

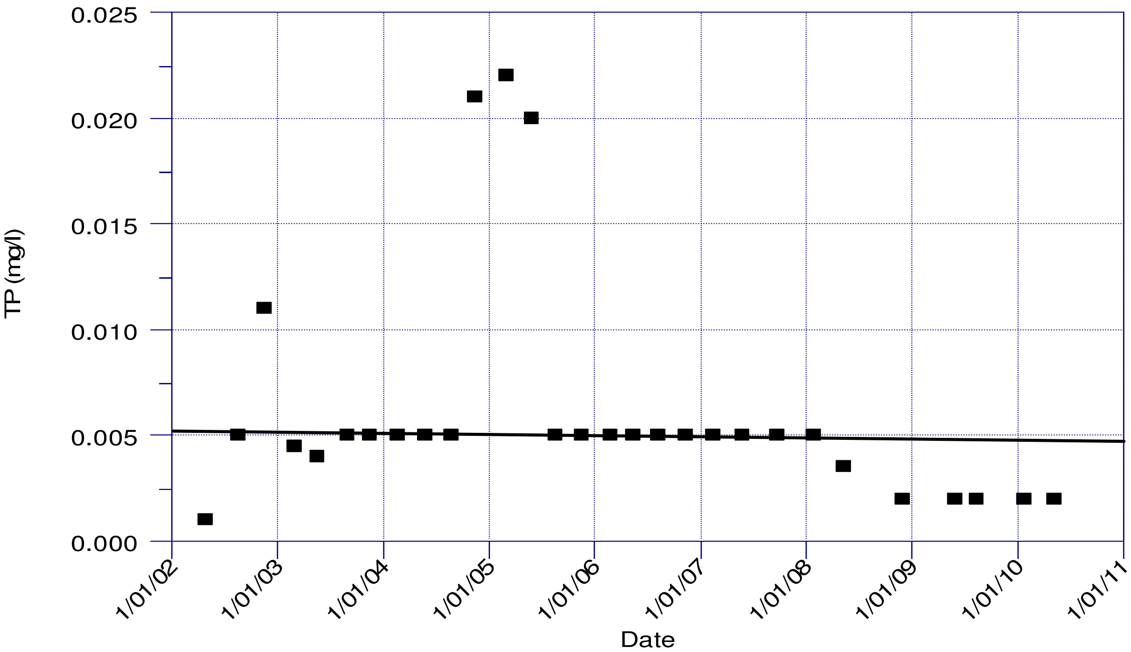

Figure 4.4: Artificial trend in total phosphorus at Lake Manapouri at Stony Point (top) due to change in detection limit (PAC=-6% p.a., p=0.02).

4.2 Lake Te Anau

In Lake Te Anau decreasing trends were observed in the TLI index, total nitrogen (TN) and turbidity. The decreasing trend in TLI index is shown in Figure 4.5, and appears to be driven by changes in the detection limit of some variables making up the TLI (i.e. TN, TP, Chl a). The data was adjusted to force consistent detection limits over time of 0.055 g/m^3, 0.002 g/m^3, and 0.0005 g/m^3 for TN, TP and Chlorophyll *a* respectively. When this was done the downward trend in TLI was no longer statistically significant (p-value = 0. 2).

The decreasing trend of TN in Lake Te Anau South Fiord is shown in Figure 4.6. Unlike the TLI trend, this decreasing trend at South Fiord and Blue Gum point was still statistically significant after the data was adjusted to force a consistent detection limit of 0.055 g/m^3.

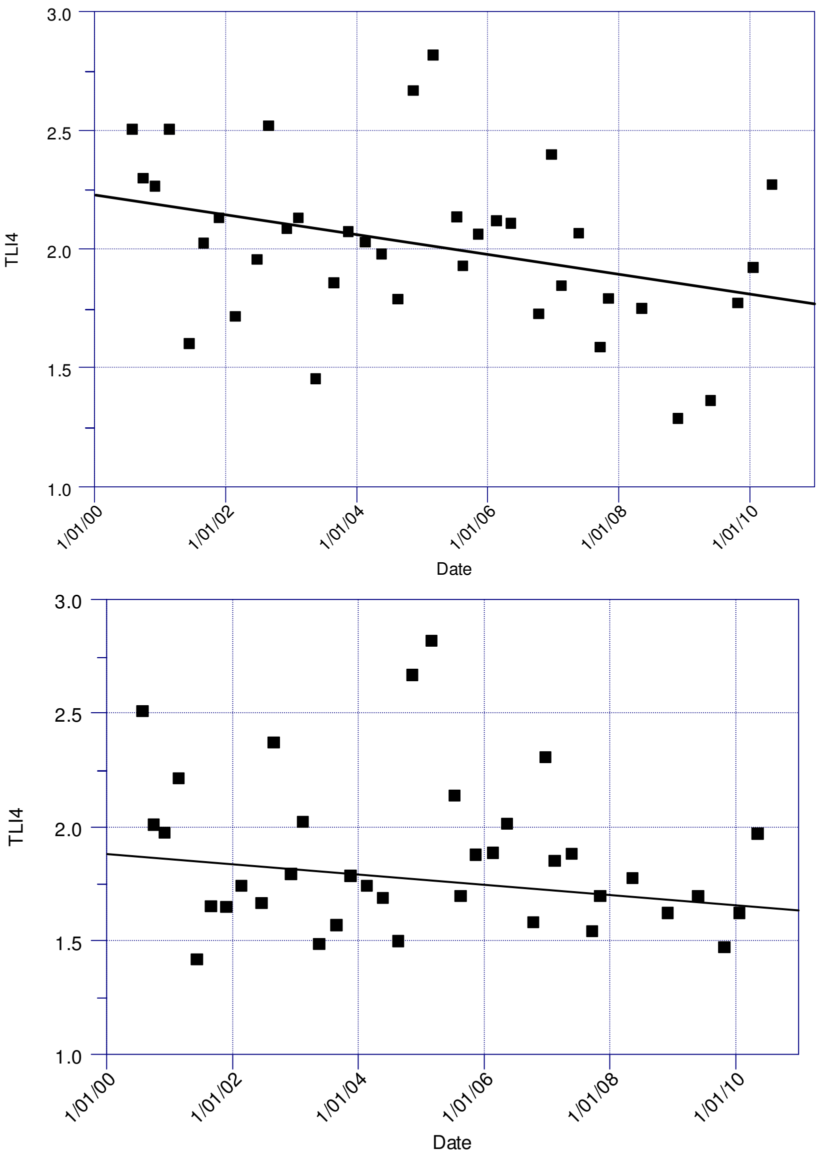

Figure 4.5: Top, an apparent trend in TLI at Lake Te Anau South Fiord (PAC=-2% p.a., p=0.02). Bottom, the trend is not significant after accounting for changes in detection limits (PAC=-1.2% p.a., p=0. 2).

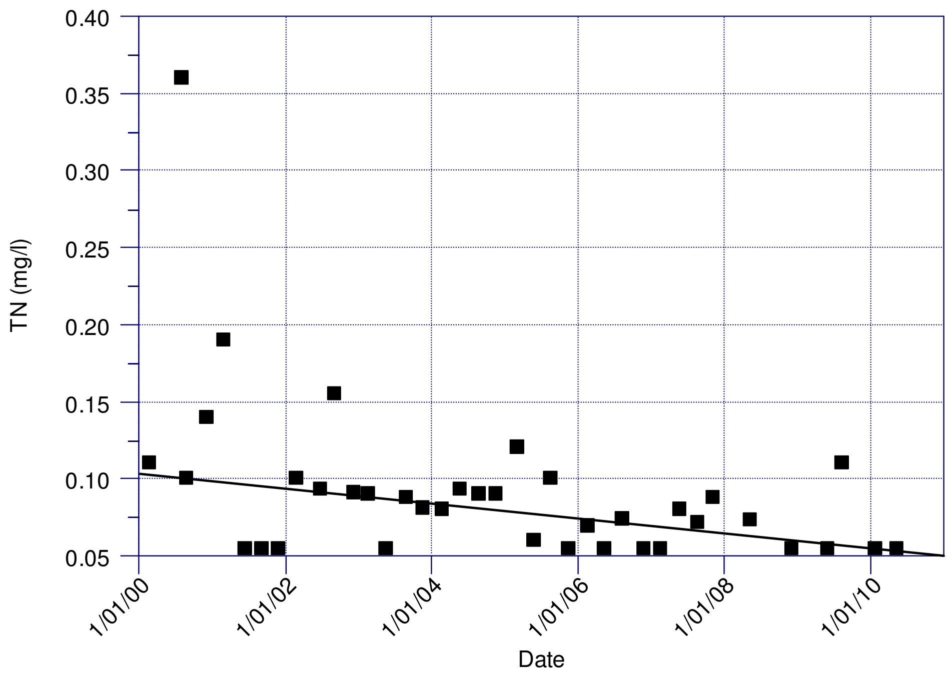

Figure 4.6: Trend in TN at Lake Te Anau South Fiord (PAC = -6% p.a., $p<0.01$). Data adjusted for consistent detection limit.

4.3 Waituna Lagoon

Data from Waituna Lagoon indicated increasing trends at some sites for TLI, TN and TP. A substantial part of the variation in TN (and hence TLI) can be explained by opening and closing of the lagoon and by using salinity (or electrical conductivity) as a covariate.

A Gam curve using EC explained 25%, 41%, 38% and 45% of the variation in TN for sites east, south, west and centre respectively. Similarly, EC explained 13%, 47%, 27% and 58% of the variation in TLI for sites east, south, west and centre respectively. After TLI and TN data was adjusted for EC as a covariate, there were no significant trends in Waituna Lagoon for TLI, TN or TP.

A trend analysis on data limited to when Waituna Lagoon was closed also found no statistically significant trend in TLI or TN at a p-value of 0.05 (i.e. 95% confidence). However, there remained a possible trend in TN at the Centre site at a p-value of 0.1 (i.e. 90% confidence). This possible trend should be treated with caution because it there is less statistical confidence that it is real and it was not observed when data was adjusted for EC.

These analyses show that apparent increasing trends in TN and TLI were mostly an artefact of the period of time the lagoon was open and closed in different years. This is illustrated by changes in electrical conductivity shown in Figure 4.7. Electrical conductivity is high (above about 15,000 us/cm) when the lagoon is open, and lower when it is closed. Figure 4.7 shows that the data from recent years mostly occurred when the lagoon was closed, and with less dilution from seawater. The graph also show progressively increasing freshwater influence (and declining EC) each time the lagoon is closed.

In contrast to TLI and TN, limiting analysis to when the lagoon was closed revealed a significant decreasing trend in chlorophyll *a* concentrations at Waituna Lagoon south and west sites (Figure 4.8).[8]

There was a significant increasing (deteriorating) trend in TP at Waituna Lagoon Centre (see Figure 4.9). A Gam curve using turbidity explained 32%, 52%, 48% and 22% of the variation in TP for sites east, south, west and centre respectively. After applying this turbidity adjustment, the increasing TP trend remained at the Centre site and also became apparent at the West site (p=0.05). Schallenberg *et al.* (2010) used DIN:TP ratios and concluded that in the absence of other growth limiting factors Waituna Lagoon would be probably phosphorus limited; thus an increasing trend in TP in Waituna Lagoon is of particular concern. Hamill and McBride (2003) found a significant relationship between increasing phosphorus concentrations in Southland rivers and an increasing intensity of dairy farming in the catchments, and the possibility that the deteriorating trend in TP is driven by land use changes should be investigated.

No significant trend was apparent in TP when data was analysed only for periods when the lagoon was closed. Considering the poor correlation between EC and TP (explaining less than 5% of the variance at any sites) it is likely that the lack of correlation when the lagoon is closed was due to the more limited dataset reducing the power of the analysis.

Interestingly, dissolved reactive phosphorus (DRP) had a statistically significant declining (improving) trend at Waituna Lagoon South and Centre (PAC 10% and 9.3% respectively). The trend was stronger after adjusting for turbidity as a covariate (it was also apparent at the Centre site when the lagoon was closed).

No statistically significant trend was apparent at any site for nitrate-nitrite nitrogen when the lagoon was closed, however when the data was filtered to only analyse concentrations during winter (1 May to 30 September) and only for periods when the lagoon was closed, increasing nitrate concentrations were apparent at Waituna Lagoon east (p-value = 0.02, PAC=17%)[9]. Corresponding trends in TN during winter when closed were not apparent. Phytoplankton and macro-algae blooms in recent years may have reduced nitrate concentrations to lower levels during summer which would hide a trend unless seasonally filtered (see Figure 4.10).

The Department of Conservation (DoC) has commissioned monitoring of macrophytes (e.g. *Rippia* sp. and *Myriophyllum* sp.) in Waituna Lagoon since 2007 (Stevens and Robertson 2010). Stevens and Robertson (2010) concluded that there was a continuing trend towards eutrophic conditions which corroborates the deteriorating trends observed in the raw dataset for TN, TP and TLI. Specifically, there was a decline in the condition of the *Ruppia* beds, decreased sediment oxygen, and rotting organic matter on the sediment surface. The monitoring also found much greater abundance of the nuisance macro-algae *Enteromorpha* sp. and *Bachelotia* sp. in March 2009 and February 2010 compared to March 2007.

A different way to analyse the data is to look at changes in variable concentrations over time, each time the lagoon is closed. The red arrows in Figure 4.9 indicate rates of TP

[8] The same trend was apparent at these sites when the data was adjusted for EC as a covariate, despite EC explaining only 10% and 5% of the variation at Waituna Lagoon south and west respectively.

[9] Trends were also apparent at the Centre and East sites at a p-value of <0.1.

loading to the water column when the lagoon is closed. Prior to 2006 the rate of nutrient loading appears to have been small, while since 2006 the TP concentrations have increased at a much faster rate.

The rate of change in chlorophyll *a* concentrations tells a more complex story (Figure 4.8). Prior to 2006 there phytoplankton (measured as chlorophyll *a*) appeared to change little over time when the lagoon was closed, in the summer of 2007 and 2008 chlorophyll *a* increased rapidly after the lagoon was closed (with a bloom in 2007), but open water chlorophyll *a* has not responded to lagoon closure or increasing TP concentrations in subsequent years. One possible explanation of this decoupling of TP and chlorophyll *a* concentrations is possible competition for nutrients between planktonic phytoplankton (measured with chlorophyll *a* concentration) and macro-algae attached to substrate and plants. Stevens and Robertson (2010) found blooms of macro-algae in 2009 and 2010 but not in 2007. Macro-algae competition for nutrients may explain the low rate of increase in chlorophyll *a* in 2009 and 2010, the declining trend in dissolved reactive phosphorus (counter to the trend in TP), and the obscured trend of increasing nitrate until filtered for just the winter season.

Given the complex interactions controlling water quality in Waituna Lagoon, it is important to maintain at least monthly frequency in water quality sampling. Filtering data to periods of when the lagoon is either open or closed reduces the power of the analysis to detect trends and quarterly analysis would further reduce this power.

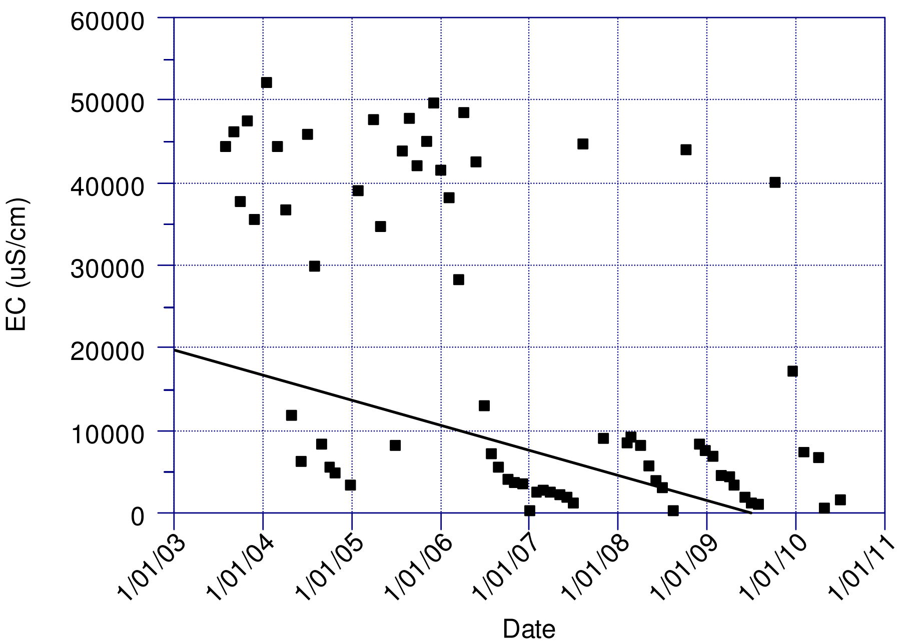

Figure 4.7: Trend in EC in Waituna Lagoon centre (PAC = -37% p.a., p <0.01), indicating that in recent years the data is biased towards when the lagoon is closed (low EC) compared to data before 2006.

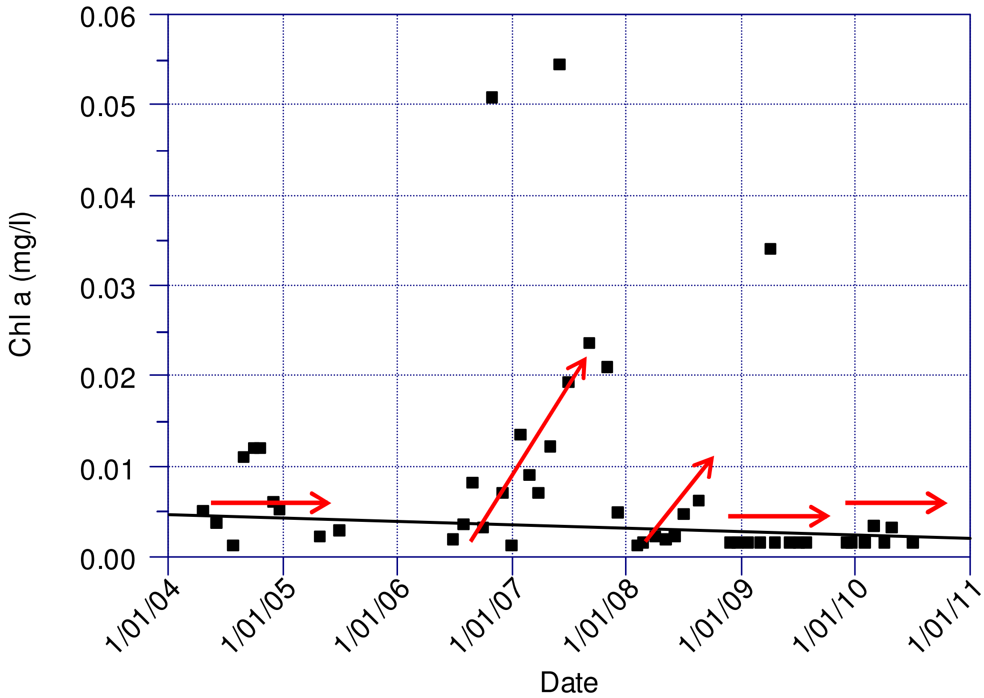

Figure 4.8: Trend in Chlorophyll *a* in Waituna Lagoon South, when the lagoon is closed (PAC = -12% p.a., *p* =0.03). Red arrows indicate changes in chlorophyll *a* during periods when the lagoon was closed.

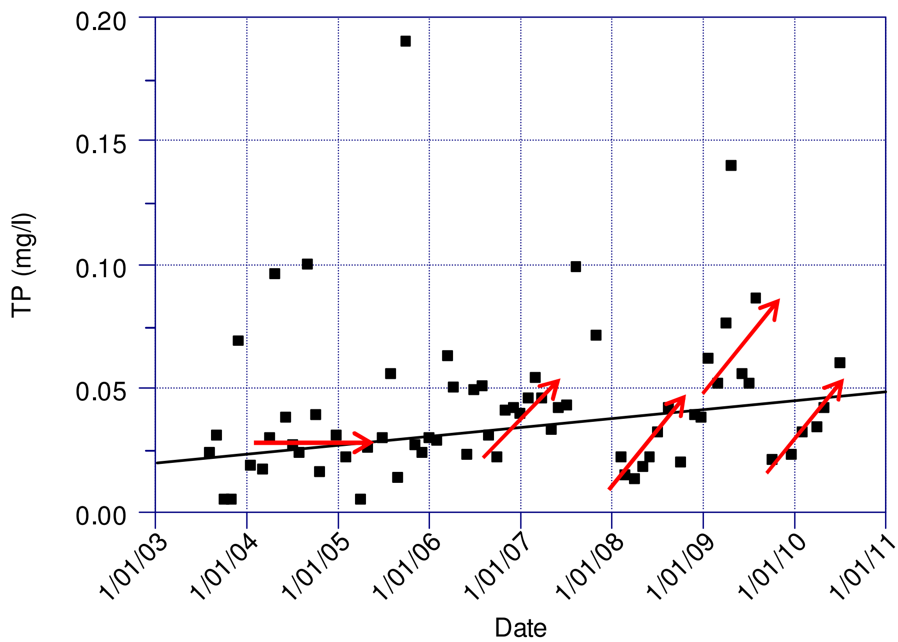

Figure 4.9: Trend in TP in Waituna Lagoon Centre (PAC = 10% p.a., *p* =0.01). Trend still significant after adjusting for turbidity as a covariate. Red arrows indicate changes in TP during periods when the lagoon was closed.

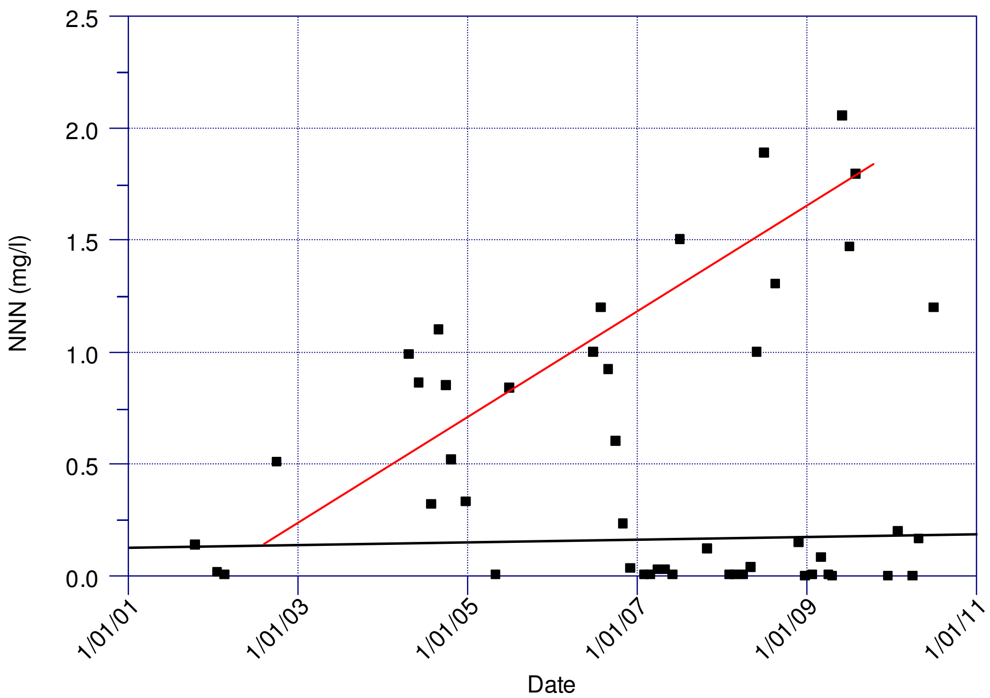

Figure 4.10: Trend in nitrate-nitrite nitrogen in Waituna Lagoon Centre when closed. The trend was statistically significant for winter data regardless of closed regime (red trend line) suggesting algae or plant uptake during summer.

4.4 Summary of trend results

The key results from trend analysis is summarised for each lake below.

Lake Manapouri:

- A strong decreasing (deteriorating) trend in Secchi depth since about 2005. This is possibly part of a cyclic pattern but should be carefully monitored in case it is due to external pressures.
- A change in detection limits have caused artificial trends in TP and probably turbidity.
- There is a limited ability to detect trends due to a large number of values below detection limit, consequently trends could be occurring without being detected.

Lake Te Anau

- A downward (improving) trend in TN at both Blue Gum Point and in South Fiord.
- A change in detection limits have caused artificial downward trend in TLI (South Fiord) and probably turbidity.

- There is a limited ability to detect trends due to a large number of values below detection limit. Consequently trends could be occurring without being detected.

Waituna Lagoon

- Analysis of raw data showed increasing trends at some sites for TLI, TN and TP, but the trend in TLI and TN were not significant after adjusting for whether the lagoon was open or closed.

- After adjusting for whether the lagoon was open or closed there was still an increasing (deteriorating) trend in TP at Waituna Lagoon sites Centre and West. This is especially concerning because Waituna Lagoon is predominantly P limited, and should be carefully monitored.

- A downward (improving) trend in chlorophyll *a* at Waituna Lagoon sites South and West was apparent after adjusting data for open and closed regime. Blooms of macroalgae (attached to sediments and plants) have been recorded in recent years (i.e. 2009 and 2010) and this may have suppressed the growth of planktonic algae (and chlorophyll *a* concentrations) by competing for nutrients.

- There was a tread of decreasing (improving) dissolved reactive phosphorus at several sites. This may be explained by utilisation of readily available nutrients by blooms of benthic macro-algae in 2009 and 2010.

- More periods of lagoon closure since ~2006 have caused an apparent increase (deterioration) in TN.

- Concentrations of nitrate during winter have increased at some sites, independent of the ‘open and closed’ regime. Summer nitrate concentrations are still often low, probably due to plant and algae utilisation.

- Maintaining at least monthly sampling of Waituna Lagoon is important to ensure any trend analysis has sufficient power after making other adjustments (e.g. for EC, turbidity or ‘open and closed’ regime).

5 Lake flipping: Implications for Waituna Lagoon

5.1 What is lake flipping?

Lake flipping refers to a phenomenon where lakes undergo a regime shift between a macrophyte-dominated clear water state and a devegetated, turbid water state. There are at least 37 lakes in New Zealand that have undergone shifts between clear water and turbid states and/or vice versa; they occur from Northland to Otago, but more commonly in shallow lakes in the North Island (Schallenberg and Sorrell 2009).

A collapse of macrophyte populations in shallow lakes is typically followed by deterioration in water quality. For example, in Lake Ellesmere macrophyte beds collapsed in 1968 following a severe storm, since the loss turbidity and phytoplankton biomass in Lake Ellesmere have remained high (Schallenberg *et al* 2010). If macrophytes establish again then water quality also improves, but often macrophytes do not reestablish (Hamill 2006);

These alternative states both have positive ecological feedbacks maintaining their equilibria. In the turbid state, light penetration may limit macrophytes from establishing again, allowing more re-suspension of sediment by wave energy, which exacerbates the poor light penetration for macrophyte growth. Sediment suspension from the bottom also increases the loading of phosphorus and nitrogen in the water column, potentially favouring phytoplankton growth over macrophytes. In contrast, the presence of macrophytes reduces turbulence and thus improves light penetration. A shift from a clear to turbid state can be triggered by a number of factors including land use change, feeding of herbivorous and benthivorous fish, grazing of waterfowl, or storms.

Schallenberg and Sorrell (2009) investigated the factors correlated with regime shifts in lakes from clear and turbid water. They found the turbid, phytoplankton-dominated state is more likely to occur in shallow New Zealand lakes as the percentage of lake catchment in pasture increases above 30% and especially once it increases above 70%. A lot (61%) of the variance in land use variables was explained by principle component axis 1 scores (PCA 1), expressed in the following formula:

PCA1 = -0.0915(alpine) + 0.8295(exotic forest) + 0.5427(native forest) + 0.0293(other) – 1.0677(pasture) – 0.2537(urban) + 1.0959(forest)

Where each land use variable is the square-root transformed % catchment cover.

A regression model was then developed that predicted the percentage of lakes that exhibited regime shifts in relation to PCA 1. This was:

% regime-shifting lakes = 29.7 - 27.3(PCA 1) (r^2=0.92, P<0.001)

Other variables predicting the likelihood of a regime-shifting lake were:

- Mean annual air temperature > 10.5 °C;
- Occurrence of the exotic macrophyte *Egeria densa;*
- Presence of herbivorous (e.g. rudd, koi carp) and benthic feeding fish (e.g. catfish) (80% of lakes with two of these species exhibited regime shifts).

A schematic of how small lakes respond to increasing eutrophication is shown in Figure 5.1. Lakes in a phased of "increasing nutrients", like Waituna Lagoon, are particularly vulnerable to 'flipping'.

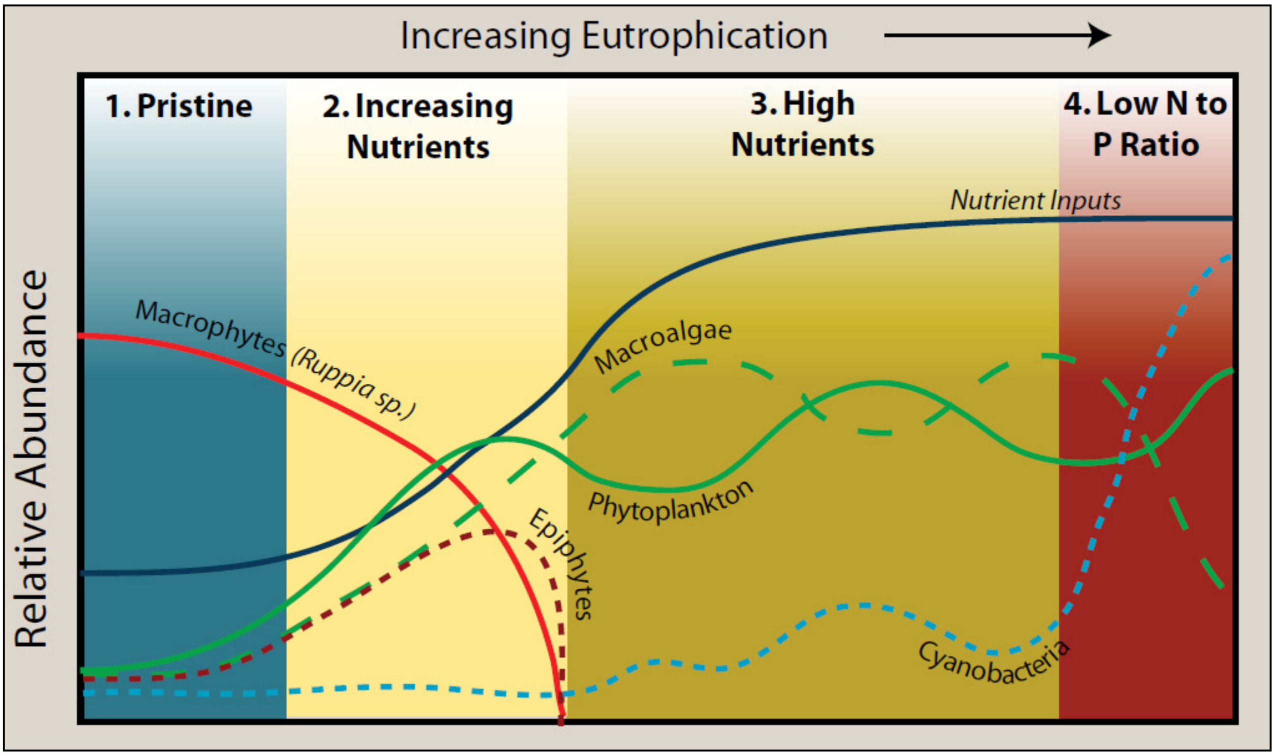

Figure 5.1: Generalised lake response to increasing eutrophication. Waituna Lagoon appears to be entering phase 2 'increasing nutrients' (from Stevens and Robertson 2010), adapted from De Wit *et al*. 2001).

5.2 Will Waituna Lagoon flip?

Waituna Lagoon is dominated by the native aquatic macrophytes *Ruppia polycarpa* (in shallow areas), *Ruppia megacarpa(* in deeper areas), and *Myriophyllum triphyllum* (to a lesser extent). Stevens and Robertson (2007) found about one third of the lagoon had moderate-high cover (>20% cover) and about two thirds with some (>1%) cover. Most *Ruppia* sp. cover was in the eastern part of the lagoon and in areas of the lagoon sheltered from wave and wind disturbance. The lower depth threshold of *Ruppia* sp. in Waituna Lagoon is probably caused by light limitation (Schallenberg and Tyrrell 2006).

The macrophyte, *Ruppia megacarpa*, is a keystone species in Waituna Lagoon because of its importance as a habitat for invertebrates and fish, as a food source for invertebrates and waterfowl, and because of its role in regulating water quality.

The likelihood of Waituna Lagoon exhibiting a regime shift was assessed using the relationship between land use variables and % regime-shifting lakes developed by Schallenberg and Sorrell (2009).[10] To apply this relationship to an individual lake it was

[10] Land use data was derived from the Waters of National Importance Database.

assumed that the percentage of regime shifting lakes calculated by Schallenberg and Sorrell (2009) reflects the probably that an individual lake will undergo a regime shift. This predicted that Waituna Lagoon has a 40% likelihood of being a regime shifting lake based on land use variables, however, if the % pasture in the catchment increased from its current 65% to 71%, the likelihood of Waituna Lagoon have a regime shift would increase to 70-80% (depending on the type of land being converted).

The likelihood of Waituna Lagoon flipping would significantly increase if the trend of increasing phosphorus concentrations continues. It will also increase if:

- There was an increase in the percentage of pasture in the catchment, an increase in the intensity of land use or a loss of native plant cover resulting in increased loads of nutrient or sediments;
- The extent of native macrophyte cover was reduced by changes in the salinity or light regime;
- The lagoon was invaded by exotic macrophytes;
- The lagoon or upstream catchment was invaded by coarse fish species (e.g. catfish, goldfish, rudd, tench, or koi carp). Currently the only exotic fish species in the lagoon are brown trout and perch (*Perca fluviatilis*) (Thompson and Ryder 2003).

Secchi depth can be used as a surrogate for the extent of light penetration into a lake required for plant growth. Waituna Lagoon has a median Secchi depth of about 1.2 m, which is not sufficient for light to reach the bottom of the deepest parts of the lagoon. A decline in water clarity could impact on the cover of *Ruppia* sp. in deeper parts of the lagoon, potentially causing the lagoon to flip to a turbid state. If this were to occur it could mean the loss of tall water plants (*Ruppia* sp.) and relatively clear water, as the water becomes increasingly turbid with suspended sediment and phytoplankton, like that in Lake Ellesmere.

Effective *Ruppia* sp. recruitment is favoured by conditions of low salinity followed by high light. It is possible that allowing extended periods in which the lagoon is open would improve water quality in the short term but create unfavourable saline conditions for *Ruppia* sp. germination and hence be detrimental in the long term. Schallenberg & Tyrrell (2006) found that that in the event of the lagoon did 'flip' to a phytoplankton-dominated state, the present light climate and opening regime would not allow the regrowth of *Ruppia* sp. in Waituna Lagoon.

6 Recommendations

This work have identified a number of ways where lake water quality monitoring in Southland could be improved, these include:

- Further investigate the water quality in small coastal lakes and the effect of surrounding land use. A limited amount of spot samples taken from small coastal lakes suggest that they are in a eutrophic – supertrophic condition.
- Investigate changing analytical methods or laboratories to achieve better detection limits for TSS, VSS, TP, TN and chlorophyll a. There are a large number of nutrient and suspended sediment samples from Lake Te Anau and Lake Manapouri that are below detection limit. This presents a problem for accurately assessing the state of the lake and seriously limits the ability of the monitoring to detect water quality trends. Further improving the low level detection limit of samples collected from Lake Te Anau and Lake Manapouri is absolutely critical to ensure trends can be detected and to compare against the standard for Natural State.
- Closely monitor the change in Secchi depth in Lake Manapouri and Lake Te Anau, and further investigate why this may be occurring, including a back flow of water from the Mararoa River, land use changes, changes in rainfall patterns impacting on humic staining in the lake, and the consistency of the Secchi depth monitoring technique used.
- Increase the frequency of monitoring Lake Te Anau and Lake Manapouri to monthly to improve ability to detect trends. Resources could be freed for more frequent monitoring by suspending monitoring of deep water sites.
- Maintain at least monthly sampling of Waituna Lagoon. This is important to ensure any trend analysis has sufficient power after making other adjustments for the ‘open and closed’ regime.
- Measure Secchi depth on all sample occasions in Waituna Lagoon.
- Include volatile suspended solids as a variable to monitor in Waituna Lagoon. This will allow calculation of inorganic suspended solids and help distinguish the effect of re-suspension of sediments on measured concentrations of total phosphorus.
- Consider reducing the number of sites monitored on each lake to free resources to allow more frequent monitoring e.g. a return to monthly sampling for Lakes Manapouri and Te Anau.
- Investigate nutrient limitation in Waituna Lagoon using bioassay experiments.
- Support the continued monitoring of macro-algae in Waituna Lagoon and consider more frequent (e.g. monthly) assessment of macro-algae cover at selected sites.
- Investigate catchment land uses and activities around Waituna Lagoon that may be contributing to the observed increase in phosphorus in the lagoon.
- Consider setting nitrogen and phosphorus load targets for Waituna Lagoon.

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Abbreviations

CHL a	Chlorophyll *a*
DO	Dissolved oxygen concentration
DRP	Dissolved reactive phosphorus
CCME WQI	Canadian Council of Ministers of the Environment Water Quality Index
EC	Electrical conductivity
LakeSPI	Lake Submerged Plant Index
NH4-N	Ammoniacal nitrogen
NNN	Oxidized nitrogen, NO_3 and NO_2
PAC	Percent Annual Change
Secchi	Secchi depth transparency
SOE	State of Environment Report
TLI	Trophic Level Index (from Burns *et al* (2000))
TN	Total nitrogen
TP	Total phosphorus
TSS	Total suspended solids
TURB	Turbidity
VSS	Volatile suspended solids

Appendix 1: The CCME WQI Equation

The CCME Water Quality Index, version 1.0 (CCME WQI 1.0) takes the form:

$$CCMEWQI = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right) \quad (1)$$

Where:

F_1 represents the percentage of variables that depart from their objectives at least once, relative to the total number of variables measured:

$$F_1 = \left(\frac{\text{Number of failed variables}}{\text{Total number of variables}} \right) \times 100 \quad (2)$$

F_2 represents the percentage of failed individual tests:

$$F_2 = \left(\frac{\text{Number of failed tests}}{\text{Total number of tests}} \right) \times 100 \quad (3)$$

F_3 is an asymptotic capping function that scales the normalized sum of the excursions from objectives (*nse*) to yield a range between 0 and 100.

$$F_3 = \left(\frac{nse}{0.01 nse + 0.01} \right) \quad (4)$$

The collective amount by which individual tests are out of compliance is calculated by summing the departures of individual tests from their objectives and dividing by the total number of tests (both those meeting objectives and those departing from objectives). The *nse* variable is, expressed as:

$$nse = \frac{\sum_{i=1}^{n} departure_i}{\#\ of\ tests} \quad (5)$$

For the cases in which the test value must not exceed the objective:

$$departure_i = \left(\frac{FailedTest_i}{Objective_j} \right) - 1 \quad (6)$$

For the cases in which the test value must not fall below the objective:

$$departure_i = \left(\frac{Objective_j}{FailedTest_i} \right) - 1 \quad (7)$$

For the cases in which the objective is zero

$$departure_i = FailedTest_i \quad (8)$$

Departures are equivalent to the number of times by which a concentration is greater than (or less than) the objective.

Appendix 2: Summary results for all sites including bottom water samples

Site	n	Water Temp (oC)	pH	EC (uS/cm)	DO (mg/L)	TN (mg/l)	NNN (mg/l)	NH4-N (mg/l)	TP (mg/l)	DRP (mg/l)	Chl a (mg/l)	Turbidity (NTU)	Secchi (m)	VSS (mg/l)	TSS (mg/l)	TLI4	TLI3
Manapouri at Frazers Beach Top	37	11.0	7.1	31	10.5	0.055	0.032	0.005	0.005	0.002	0.0015	0.3	11.2	1.3	1.3	2.0	
Manapouri at Frazers beach bottom	37	11.0	7.2	31	10.5	0.055	0.033	0.005	0.005	0.002		0.3					
Manapouri at Stony Point Top	35	10.9	7.2	31	10.3	0.055	0.034	0.005	0.005	0.002	0.0015	0.3	11.7	1.3	1.3	2.0	
Manapouri at Stony Point bottom	38	9.2	7.0	30	10.4	0.082	0.049	0.005	0.005	0.002		0.3					
Manapouri at Pomona Island Top	36	10.5	7.1	30	10.2	0.048	0.033	0.005	0.005	0.002	0.0015	0.4	11.9	1.3	1.3	2.0	
Manapouri at Pomona Is Bottom	38	9.0	6.9	30	10.2	0.081	0.048	0.005	0.005	0.002		0.2					
Te Anau Blue Gum Point Top	37	9.8	7.2	31	10.2	0.055	0.034	0.005	0.005	0.002	0.0011	0.4	11.6	1.3	1.3	2.0	
Te Anau Blue Gum Point bottom	37	9.9	7.1	31	10.2	0.055	0.041	0.005	0.005	0.002		0.3					
Te Anau South Fiord Top	38	10.1	7.2	31	10.5	0.055	0.036	0.005	0.005	0.002	0.0009	0.3	12.1	0.6	1.3	1.9	
Te Anau South Fiord bottom	39	9.7	7.1	31	10.4	0.083	0.046	0.005	0.005	0.002		0.3					
Waituna Lagoon east	45	12.7	7.8	5600	9.8	0.750	0.022	0.014	0.036	0.002	0.0021	5.8			4.3		4.3
Waituna Lagoon south	54	12.2	7.8	7870	9.3	0.745	0.054	0.015	0.035	0.005	0.0022	5.8			4.5		4.4
Waituna Lagoon centre	49	11.9	7.7	6780	9.4	0.760	0.040	0.014	0.041	0.005	0.0032	5.7			5.2		4.6
Waituna Lagoon west	54	11.9	7.8	7250	9.1	0.800	0.129	0.014	0.040	0.005	0.0024	7.0			7.0		4.5
Waituna Lagoon east closed	37	12.9	7.8	4300	10.1	0.780	0.018	0.012	0.038	0.002	0.0020	6.0			4.2		4.3
Waituna Lagoon south closed	39	12.8	7.8	4240	10.0	0.800	0.034	0.014	0.036	0.002	0.0022	5.3			4.1		4.6
Waituna Lagoon centre closed	35	12.7	7.6	3860	10.2	0.930	0.103	0.013	0.042	0.005	0.0037	6.3			5.1		4.7
Waituna Lagoon west closed	39	12.5	7.7	4110	9.3	1.000	0.118	0.012	0.040	0.005	0.0024	6.7			6.4		4.7
Forest Lake	1		4.9	316		2.000	0.016	0.065	0.710	0.480							
Lake George	1	13.2	7.7	192	9.9	1.100	0.005	0.010	0.074	0.008		30.0					
Lake Vincent East top	2	12.8	8.3	287	11.7	0.780	0.018	0.005	0.030	0.004	0.0081	3.0	1.5				4.7
Lake Vincent West top	2	12.5	7.8	292	10.9	0.625	0.005	0.005	0.124	0.005		2.5	1.8				5.0
Lake Vincent West bottom	2	12.5	7.9	286	11.0	0.585	0.005	0.005	0.023	0.026		2.7					
Reservoir South	3	10.1	7.7		11.1	0.670	0.005	0.005	0.040	0.003	0.0076	8.2	0.8				5.0
Resevoir North	3	10.0	7.6	275	10.6	0.680	0.005	0.005	0.040	0.014	0.0051	9.2	0.8				4.9

Note:
Data for Forest Lake, Lake George, Lake Vincent and the Reservoir should be treated with caution beascause it is based on few spot samples in 2000 & 2007.
There were insuffiecent measurements to provide reliable Secchi depth data for Waituna Lagoon.
TSS was based on a limited dataset of 17 samples since 2008.