Trophic Level Index Review of targets and variability for the Rotorua Lakes

Prepared for:

Bay of Plenty Regional Council

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Executive summary

Introduction

The Regional Natural Resources Plan (**RNRP**) of Bay of Plenty Regional Council (**BOPRC**) set water quality targets, expressed using the Trophic Level Index (**TLI**), for each of the twelve Rotorua Te Arawa lakes. These TLI targets were set for most lakes to achieve historical water quality conditions that occurred in the early 1990's or earlier. Considerable water quality monitoring data has been collected since these TLI targets were set, which provides an opportunity to better understand the long-term, interannual variability in lake water quality, and consider how this variability can be recognised in TLI targets.

This report provides a science review of TLI data and the TLI targets for each of the 12 Rotorua Te Arawa lakes. It includes:

- Adjusting the phosphorus (**P**) data to account for laboratory changes. This addresses historic analytical issues associated with and P data due to changes in laboratory methods and the interference of arsenic (**As**) and silica (**Si**) when measuring phosphorus by some methods.
- Analysis of trends in the TLI each lake using a seasonal Kendall trend test;
- Assessment of TLI state and potential climatic drivers of temporal variability, and
- A review of the TLI targets along with options to express the TLI scores and/or TLI targets to better account for their natural variability.

Laboratory method change

The report discusses the effect of changes in analytical method on total phosphorus (**TP**) and total nitrogen (**TN**) results (**Appendix B**). TP concentrations from the period August 2010 to September 2019 (inclusive) were higher in many lakes due to additive interface in the analytical method by silica and arsenic. A new analytical method for TP was adopted in October 2019 that addressed these issues. The additive interference was strongest in lakes with a high Si to TP ratio or with high As concentrations (i.e. Rotomahana, Tarawera, Rotomā, Ōkataina and Rotoehu). A period of inter-calibration of the two methods allowed development of lake-specific formulae to correct data during the period when analyses were potentially biased. However, for some lakes, the corrected dataset may still have apparent variation in TP results caused by interannual and seasonal variations in Si.

In November 2009, the BOPRC laboratory changed its method for analysing TN in water samples. The new method had a lower detection limit and more precise results. However, the new method (**TN-A**) is known to have a potential low bias compared to the old method (**TN-K**). The water quality data being considered when setting the TLI targets mostly used the TN-K method for analysing TN. Thus, it is possible that the TLI targets are high (i.e. less stringent) compared to a TLI determined using current monitoring TN-A data. However, this issue does not justify a change in the TLI targets because there remains uncertainty about the relative bias between the two methods when applied to the Rotorua lakes; nevertheless, it may justify being stringent when setting triggers for action.

Influence of the TLI formulae

The report examines the influence of different formula used to calculate TLI and particularly the Secchi depth component (**TL-s**) (**Appendix C**). The formula used in the BOPRC Lake Watch software has been adopted for this report and produced similar results to those using the formula in Burns et al. (2000). It is not clear what TL-s formula was used when calculating TLI values during the process of setting the TLI targets, although it is likely to have been from Burns et al. (2000). BOPRC could consider changing to use the Burns et al. (2000) TL-s formula to help with national consistency in reporting results, but the difference in TLI scores is very small (*ca*. 1.3%).

Influence of TLI calculation method

The precise method used to calculate the TLI influences the results. Burns (2000) specifies calculating TLI by logging annual mean values ("log of means"), but an alternative method often used to allow trend analysis is to calculate TLI for each separate sample occasion and average for each year/period ("mean of logs").

The "mean of logs" method results in lower TLI scores when the dataset is skewed to the right. The "mean of logs" method resulted in the annual TLI being <u>lower</u> for all of the Te Arawa lakes by 0.7% to 3.7% compared to the "log of means" method, with the largest difference for Lake Ōkaro (0.21 TLI units and 3.7 %). Unlike other variables, for Secchi depth (TL-s) the "mean of logs" method results in <u>higher</u> annual TLI scores because the Secchi depth distribution tends to be negatively skewed. These differences emphasise the importance of following a consistent method when calculating TLI scores for the purpose of reporting against target values.

Current lake water quality

Eight lakes exceed their TLI targets for the 3-year period ending July 2021 (plus Rotoiti Okawa Bay). However only four lakes currently exceed the requirements in the Regional Natural Resource Plan (**RNRP**) for setting Action Plans (i.e. the 3-year moving average TLI exceeds its target TLI by 0.2 for two consecutive years); these lakes are: Lakes Rotoehu, Rotoiti, Rotokakahi and Tikitapu (**Table 1**).

A comparison with the NPS-FM numerical bands for lake ecosystem health identified two lakes (Ōkaro and Rotoehu) in the "D" band below the bottom-line. This was due to high maximum chlorophyll-*a* values indicative of algal blooms

Table 1: Lake TLI state compared to targets for July 2020-2021 and recent 3-year periods. Shaded cells do not meet the TLI target, bolded numbers exceed the Target by more than 0.2 TLI units.

Lake	TLI Target	TLI 2021	TLI 3-yr mean 2019-21	TLI 3-yr mean 2018-20	Trophic state	Mean (July 2019 - July 2021) TN (µg/L)	TP (µg/L)	Chl-*a* (µg/L)	Secchi (m)
Ōkāreka	3.0	3.1	3.1	**3.2**	mesotrophic	180	7.9	3.1	7.8
Ōkaro	5.0	4.4	4.6	4.9	eutrophic	624	43.1	11.9	4.1
Ōkataina	2.6	2.7	2.6	2.7	oligotrophic	99	6.5	1.9	10.4
Rerewhakaaitu	3.6	3.3	3.7	**3.9**	mesotrophic	377	10.5	4.9	5.4
Rotoehu	3.9	4.3	**4.7**	**4.8**	eutrophic	485	37.2	17.1	2.4
Rotoiti	3.5	3.7	**3.7**	**3.7**	mesotrophic	176	23.1	5.7	6.1
Rotoiti Okawa Bay		4.7	4.5	4.4	eutrophic	367	40.6	11.1	3.2
Rotokakahi Outlet	3.1	3.4	**3.5**	**3.6**	mesotrophic	212	13.1	3.8	4.8 *
Rotomā	2.3	2.3	2.4	2.4	oligotrophic	115	4.6	1.2	12.0
Rotomahana	3.9	3.5	3.6	3.8	mesotrophic	207	22.2	3.4	5.4
Rotorua	4.2	4.4	4.2	4.2	eutrophic	310	20.7	10.9	3.1
Tarawera	2.6	2.7	2.7	2.8	oligotrophic	89	9.5	1.5	8.7
Tikitapu	2.7	3.2	**3.0**	**2.9**	oligotrophic	179	4.7	2.5	5.8

TLI target from the Regional Water & Land Plan

Rotokakahi was samped at outlet (Te Wairoa Stream) to calculate TLI3. Secchi est. from black disc.

Water quality trends over time

The confidence and direction of lake water quality trends were determined for three time-periods (1991 – 2021, 2001 - 2021 and 2010 – 2021 inclusive). For trends identified as "very likely" (Sen slope P-value ≤0.05), the 31-year (1991-2021) and the 21-year (2001-2021) time-periods both had seven lakes with decreasing (improving) TLI and one lake (Rerewhakaaitu) with increasing (worsening) TLI. The most recent 12-year (2010-2021) time-period had two lakes (Rerewhakaaitu, Rotokakahi outlet) with decreasing (improving) TLI and three lakes (Rotoehu, Rotoiti Okawa Bay and Rotomā) with increasing (worsening) TLI (**Table 2**).

Over the long term (31-year and 21-year periods) there were seven lakes with decreasing TLI and one lake with increasing TLI. Lakes that had a "very likely" decrease (improvement) in each of the individual TLI variables (TL-n, TL-p, TL-c, TL-s) over the long term were: Ōkaro, Ōkataina, and Rotorua. The strong improving trends in Lake Ōkaro and Lake Rotorua reflect the intensive interventions to improve the water quality in these lakes.

Table 2: Summary of TLI trends for different time periods. Arrows indicate the trend confidence and direction as follows: “very likely increasing” ↑ , “likely increasing” ↗, “uncertain” → , “likely decreasing” ↘, and “very likely decreasing” ↓. Lakes that show a step change in TN in late 2009 are identified.

	1991 - 2021 incl.		2001 - 2021 incl.		2010 - 2021 incl.		TN ⇓
Lake	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**	**2009/10**
Ōkāreka	→	0.0	→	0.1	→	0.0	Y
Ōkaro	↓	-0.8	↓	-0.9	↘	-0.6	
Ōkataina	↓	-0.5	↓	-0.6	→	-0.1	Y
Rerewhakaaitu	↑	0.2	↑	0.2	↓	-0.7	
Rotoehu	↓	-0.3	↓	-0.2	↑	1.4	
Rotoiti	↓	-0.2	↓	-0.5	↗	0.3	Y
Rotoiti Okawa Bay	↘	-0.2	↘	-0.2	↑	1.0	
Rotokakahi Outlet	→	0.0	→	-0.1	↓	-0.8	
Rotomā	↓	-0.3	↓	-0.3	↑	1.4	Y
Rotomahana	↓	-0.2	↓	-0.3	↘	-0.3	
Rotorua	↓	-0.5	↓	-1.0	→	0.0	Y
Tarawera	→	0.0	↘	-0.1	→	-0.1	Y
Tikitapu	↘	-0.1	↘	-0.2	↗	0.3	Y

Expression of the TLI for triggering action

The RNRP requires the development of action plans for lakes if the three-year moving average TLI exceeds the lake’s target TLI by 0.2 for two consecutive years. The approach of using a three-year moving average TLI that needs to exceed a trigger for two consecutive years, appears to provide a reasonable compromise between smoothing short-term variations in the TLI while still enabling timely action. However, a 5-year mean may be a better option to fit with the 5-year reporting periods used for Lake Rotorua. Either way, the reporting of annual means for the TLI and its components remains important when assessing water quality conditions.

The use of a uniform 0.2 TLI-unit tolerance is within the range of interannual variability in oligotrophic lakes, and thus provides a reasonable estimate of interannual variability in the absence of eutrophication. For eutrophic lakes, the interannual variability is considerably higher than 0.2 TLI-units but increasing the tolerance to match interannual variability in eutrophic lakes would risk entrenching periodically poor water quality as part of the lake target. Rather than change the tolerance, a more robust approach to account for interannual variability is to uses statistical tests over consecutive time periods (e.g., 5-year intervals), and to interpret TLI scores in the context of variability occurring in other lakes and due to climatic factors.

Correlation between lakes

Lakes that have a correlation in the interannual variation of their TLI values might be used as a psedo-control to help test if periods of variation in TLI might be due to catchment specific anthropogenic influence as compared to influence from climatic variation or large scale landuse changes. The lakes that most frequently had significant correlations in TLI with other lakes were Lakes Rotomā and

Ōkataina. Strong correlation in TLI was found between the lakes: Rotorua, Rotoiti, Rotomā and Ōkataina. This approach can be use with more confidence when the lakes being used as a control do not have a direct hydrological connection, but still should only be viewed as one of multiple lines of evidence from which to draw conclusions.

Climate drivers of temporal variability

Potential climatic drivers of inter-annual variability of TLI for each lake was assessed by comparing annualised TLI with annual climatic variables. There were strong correlations between the different climatic variables, particularly the Southern Oscillation Index (**SOI**), annual rainfall and sunshine hours.

No single climate variable had good correlations with TLI for all lakes. The climate variable that best correlated with TLI in most lakes was annual rainfall expressed as a 2-year running mean. This could be suitable for explaining interannual variation in TLI for Lakes Ōkāreka, Ōkaro, Ōkataina, Rerewhakaaitu, Rotoiti (1-yr rainfall better), and Rotomahana. TLI in Rotomā, Tarawera and Tikitapu had a negative correlation with SOI (related to TP), TLI in Rotokakahi had a positive correlation with SOI, and Rotorua TLI had a negative correlation with the water level in Rotomā (used as a proxy for groundwater levels).

The interannual variability in annual TLI showed alignment between clusters of lakes. There was moderately strong positive correlation (0.6 to 0.7) between Rotorua, Rotoiti, Rotomā and Ōkataina. There were weaker (0.5 to 0.6) but still statistically significant correlations in annual TLI between Rotoiti and Rotoehu, and between Rotomahana and Tarawera. Annual TLI from Lake Ōkaro was not statistically correlated with other lakes.

TLI Targets

For most lakes, the TLI targets set in the RNRP were based on achieving historical water quality conditions occurring in 1993/94 and 1994/95. For Lake Rotorua, the targets were based on achieving water quality state that existed in the 1960's. For Lake Ōkaro the TLI target appeared to be more pragmatic and based on achieving a "realistic" improvement (i.e. what was thought at the time to be practically achievable). During 1993/94 to 1994/95 the rainfall was relatively low, which probably contributed the relatively low TLI values observed at this time for many lakes.

For Lake Ōkaro, the annual TLI has often been within the target value 5 over the last decade, but even in years when Lake Ōkaro's annual TLI has been less than 5.0, there has been many occasions of intense summer algae blooms (e.g. chlorophyll-*a* >60 mg/m^3). Consideration could be given to setting a lower (more stringent) TLI target for Lake Ōkaro to better ensure that ensure that algae blooms do not exceed the NPS-FM bottom-line values.

Contents

1. Introduction

1.1 Water quality targets for Rotorua Te Arawa Lakes

The management of the twelve Rotorua Te Arawa lakes is directed by Bay of Plenty Regional Council (**BOPRC**) through the Regional Natural Resources Plan (**RNRP**), and the Regional Natural Resources Plan (**RNRP**). The Rotorua Te Arawa lakes are identified as “Catchments at Risk”, and Objective 11 (RL 01) of the RNRP requires that water quality of these lakes is maintained or improved to meet water quality targets, as expressed using the Trophic Level Index (**TLI**). This is achieved by developing and implementing Action Plans (RNRP RL M1 (method 41)). The development of an Action Plan (and possible regulatory measures) for a lake’s catchment is triggered when “*the 3-year moving average TLI for the lake exceeds its [target TLI] by 0.2 for two consecutive years*” (RNRP, RL M1 (Method 41) 1b(ii); RL M4 (Method 52)).

The TLI targets set in Objective 11 of the RNRP for each of the 12 Rotorua Te Arawa lakes are: Lakes Ōkāreka (3.0), Ōkaro (5.0), Ōkataina (2.6), Rerewhakaaitu (3.6), Rotoehu (3.9), Rotoiti (3.5), Rotokakahi (3.1), Rotomā (2.3), Rotomahana (3.9), Rotorua (4.2), Tarawera (2.6), and Tikitapu (2.7).

RL M1 (Method 41) sets the process for developing and implementing action plans. Action plans describe initiatives to maintain and improve lake water quality, including catchment management actions to reduce nutrients inputs.

The way in which the RNRP (RL M1) expresses the TLI trigger for Action Plans (i.e. the 3-year moving average TLI for the lake exceeds its target TLI by 0.2 for two consecutive years) helps account for natural variability and sampling error. But there may be ways to modify how the TLI is expressed to account for natural variability better. However, the reporting of annual means for the TLI and its components remains important when assessing water quality conditions.

1.2 Background to setting the TLI targets

The TLI targets set in the RNRP were based on achieving historic water quality conditions. For Lake Rotorua this was based on achieving water quality state that existed in the 1960’s; while for the other Rotorua lakes the target was equivalent to water quality in the early 1990’s. In some cases, the TLI target was based on achieving a ‘realistic’ improvement in the water quality occurring at the time (i.e. Lake Ōkaro). A more detailed description of the background on how the TLI targets were set is described in a memo by Lee (2013).

The data available at the time of setting the TLI targets in early 2000s’ was limited and often intermittent. Since that time, BOPRC has consistently undertaken monthly lake water quality sampling as part of the Natural Environment Regional Monitoring Network (**NERMN**) programme – providing comprehensive water quality data for each of the Rotorua Te Arawa lakes. The longer data record provides an opportunity to better understand the long-term changes and interannual variability in lake water quality, and consider how this variability could be accounted for in TLI targets. This analysis could support a future review of the TLI targets set in the RNRP, but this is beyond the scope of this report.

1.3 Scope of report

This report provides a science review of TLI data and the TLI targets set in Objective 11 of the RNRP for each of the Rotorua Te Arawa Lakes. This includes:

1. Collating all long-term data for each lake relevant to assessing the TLI;

2. Adjusting the phosphorus (**P**) data to account for laboratory changes. This is to address historic analytical issues associated with and P data due to changes in laboratory methods and the interference of arsenic (**As**) and silica (**Si**) when measuring phosphorus by some methods.

3. Analysis of water quality trends for each lake as measured by the TLI and its component parts;

4. Assessment of TLI state and temporal variability for each lake, and

5. Review of the TLI targets along with recommended options to express TLI targets to reduce their sensitivity to natural variability.

This report also contributes to the 2022 Plan Change 10 Science Review by updating the lakes water quality trends.

2. Method

2.1 Approach to the TLI review

The TLI data for the 12 Rotorua Te Arawa lakes was review using the following approach:

1. **Collate long term TLI data for each of the Rotorua lakes.** Water quality data was collated from BOPRC and Waikato University (Lake Rotorua). The dataset compiled by Waikato University for Lake Rotorua for modelling purposes had already been checked and this was used to provide a consistent basis of analysis. Variables of interest were the components of the TLI, namely chlorophyll-*a* (Chl-*a*), Secchi depth, total nitrogen (TN), and total phosphorus (TP) in sampled collected from the "top" water samples.

2. **Adjust data for laboratory changes.** Analytical methods for determining TN and TP concentrations changed around 2008 /2009, and this has influenced the results. For a period of about August 2010 to October 2019, the TP results of samples from most Rotorua lakes were elevated due to interference of the analysis by silica and arsenic. To address this issue, a new BOPRC laboratory method was trialled from early October 2018 and adopted in October 2019. Corrections factors were developed for each lake that were used to correct the data for the period August 2010 to October 2019. These functions were applied when reporting the TLI results in 2020 (Scholes 2020), and the same corrections were applied to TP data used in this report. A full description of the methods used in provided in **Appendix B**.

3. **TLI trends over time**. The TLI and its component parts for TN, TP, Chl-*a* and Secchi depth (**TL-n**, **TL-p**, **TL-c** and **TL-s** respectively) were calculated for each monthly sampling event, from surface samples at each of the 12 Rotorua lakes using the seasonal Kendall trend analysis over time periods of 31-years (1991-2021), 21-years (2001-2021) and 12-years (2009-2021). Few lakes had regular water quality monitoring prior to 1991, and for most lakes consistent monthly monitoring started around 2001.

4. **TLI state and temporal variability**. The variability of TLI and TLI components (TL-n, TL-p, TL-c and TL-s) was compared for each lake by:

    a. Assessing the current state expressed as the annual TLI and NPS_FM grading compared with the target. The TLI was expressed as it's component parts to better understand drivers of state and variability over time.

    b. Assessing the influence of the time period used for averaging TLI values on the interannual variability by looking at the effect of expressing TLI values as a rolling average over periods of one-year to eight-years.

    c. Assessing the influence of the method used to calculate the TLI – i.e. calculating a 'log of means' compared to a 'mean of logs'.

    d. Comparing inter-annual variability of each lake with climatic variables, including: annual rainfall, water deficit, water levels (e.g. using Rotomā as a proxy sites), and the southern oscillation index (SOI) (https://www.stats.govt.nz/indicators/el-nino-southern-oscillation).

5. Review of the TLI targets including using the analysis to explore options to express TLI scores and/or TLI targets to reduce sensitivity to natural climate variability. Currently, action plans are triggered if a lake's TLI exceeds the target TLI by 0.2 TLI units for two consecutive years, based on a three-year moving average. This report explores different ways to average scores over time (e.g. longer time periods), and the tolerance that might be set between a lake exceeding the TLI target and action being taken.

2.2 Lake monitoring sites and sample frequency

Water quality is monitored in 12 Rotorua Te Arawa lakes (**Figure 2.1, Table 2.1**). Most lakes are sampled at a single location near the deepest point. Lake Rotokakahi is an exception and is sampled at the lake outlet. Lake Rotorua is sampled in two locations, Site 2 (south of Mokoia Island) and Site 5 (north of Mokoia Island). Rotoiti is sampled in three locations, Okawa Bay, Site 3 at the narrows and Site 4 mid-lake. Site 4 was established in March 2003 to replace nearby Site 1. To enable long-term trend analyses, the data from Rotoiti Site 1 and Site 4 have been combined (location 130059 on map).

Table 2.1*: Water depth and catchment land cover of the Rotorua Te Arawa lakes (data from the NIWA Rivers Environment Surface Catchment layer).*

Lake	Max depth (m)	Lake Area (ha)	Catchment Area (ha)	% land cover Native	Exotic	Pastoral	Urban
Lake Ōkāreka	33.5	334	1,750	44	8	37	3.0
Lake Ōkaro	18	30	183	0	6	90	0
Lake Ōkataina	78.5	1,073	6,358	79	8	8.0	0
Lake Rerewhakaaitu	15.8	517	4,056	4	17	69	1.0
Lake Rotoehu	13.5	790	4,225	31	30	34	0.6
Lake Rotoiti	126	3,369	12,056	30	49	13	2.0
Lake Rotokakahi	32	440	1,860	50	21	27	1.1
Lake Rotomā	83	1,112	3,392	41	29	22	3.0
Lake Rotomahana	125	902	8,858	23	17	40	1
Lake Rotorua	45	8,048	48,204	19	18	47	8.0
Lake Tarawera	87.5	4,115	15,001	60	15	17	1.0
Lake Tikitapu	27.5	144	597	80	14	2.0	3

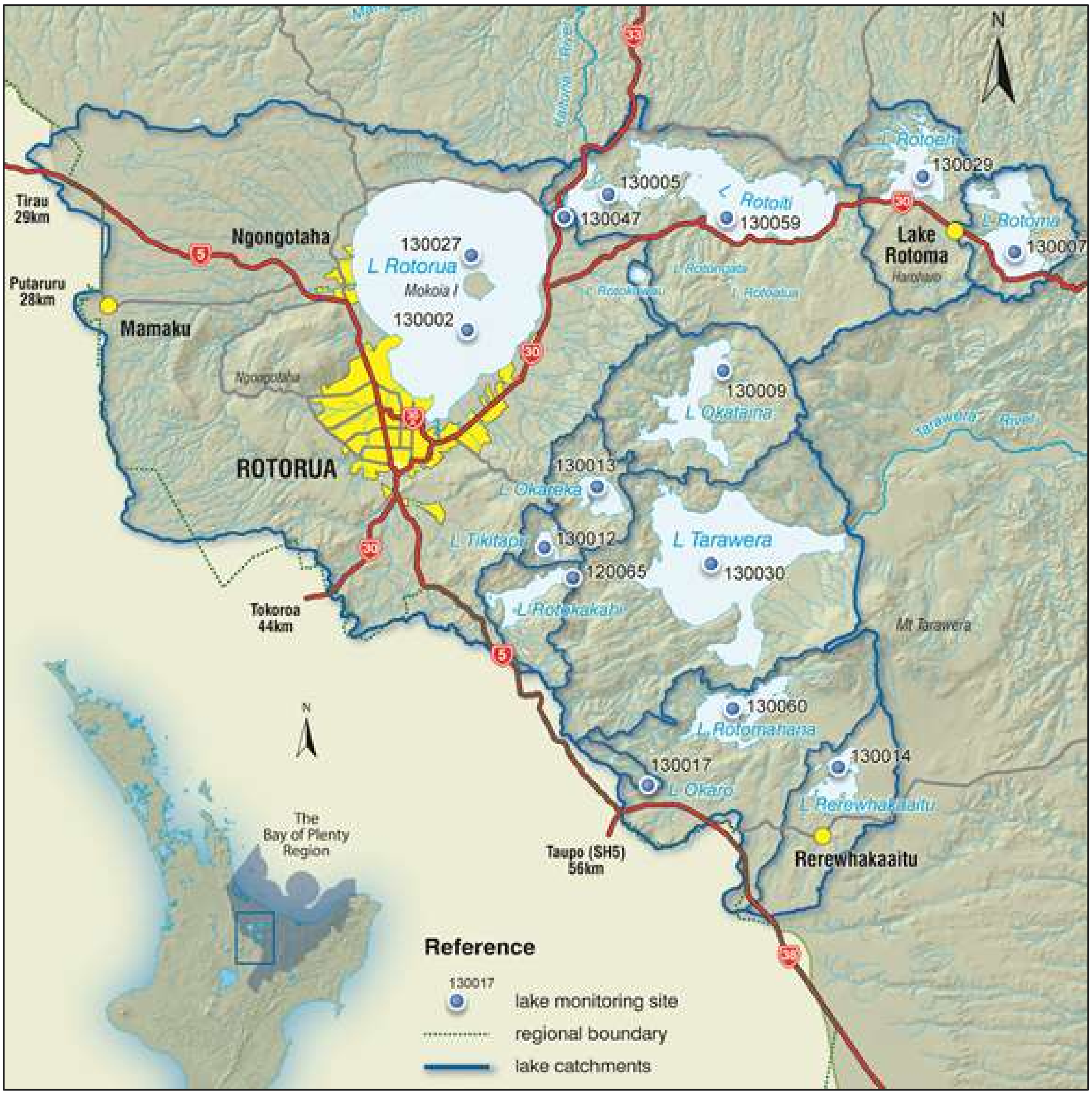


***Figure 2.1**: Location of Rotorua Lakes and water quality monitoring sites.*

2.3 Water quality dataset

2.3.1 Lake sampling methodology

Water quality sampling of the Rotorua Lakes is carried out monthly. Each lake is sampled at single or multiple deep-water sites. Profiles of temperature, dissolved oxygen, conductivity and fluorescence are recorded by a data logger with appropriate sensor arrays. Samples are collected from the top water layer (called the epilimnion if the lake is stratified) and from the bottom layer (called the hypolimnion if the lake is stratified). In most lakes a second bottom water sample is collected in the hypoxic layer consistent with Burns et al. (2000). The top sample is collected as an integrated sample over the depth of the typical epilimnion and the bottom samples as discrete samples using a Van Dorn sampler. In Lake Ōkaro additional discrete samples are collected through the depth profile.

Prior to July 2001 the depths sampled were determined by the depth of the thermocline on the day of sampling (as per Burns et al. 2000). Since July 2001, to simplify sample collection, the samples have been collected from a set depth based on a typical thermocline in different seasons (spring, summer autumn, winter).

Water quality variables collected at each lake water quality monitoring site are: water temperature (**TEMP**), pH, dissolved oxygen (**DO**), Secchi depth, electrical conductivity (**EC**), ammoniacal nitrogen (**NH_4-N**), total oxidised nitrogen (**NNN**), total nitrogen (**TN**), dissolved reactive phosphorus (**DRP**), total phosphorus (**TP**), turbidity (**TURB**), chlorophyll-*a* (**Chl-*a***), PAR light (by sensor) and *E.coli* bacteria (*E.coli*). The current laboratory analysis methods and detection limits are in **Appendix A**.

The water quality data used in this report was limited to those used in the calculation of the TLI, i.e. Secchi depth, TN, TP and Chl-*a* and collected from the epilimnion / top water layer.

2.3.2 Lake surface water quality dataset

Water quality datasets were obtained from the BOPRC Aquarius database and provided by BOPRC. Prior to analysis the water quality results were checked and processed in the following way:

- Anomalous outlying data points were removed where there was good reason to believe them to be measurement errors, this included:
  - Lake Ōkāreka there was anomalously high TN (984 ppb) on October 2013 and June 2013 (1180 ppb) that were inconsistent with other variables.
  - Lake Okaro anomalously high chlorophyll-*a* on 23 February 2006 (1370 ppb) despite other variables were not elevated.
  - Lake Rotoehu high TN (1804 ppb) and NNN (1433 ppb) on 20 Jan 2006, and high Secchi depth of 28m on 17/11/2020.
  - Lake Tarawera high TN (568 ppb) 20/7/2011 and 23/7/2003.
  - Lake Tikitapu, high turbidity value on 14 November 2006.
  - Lake Rotoiti Site 4, high Chl-*a* on 6 Oct 2004 (116 mg/m^3).
  - Rotomā high TP of 32 mg/m^3 on 19 Aug 2008
  - Lake Rerewhakaaitu high NH4-N on August 2002, September 2002 and June 2003 excluded as values much higher than TN. Similarly with a high NH4-N for Rotomahana on June 2003, and Ōkataina on December 2004.
- The majority of the dataset consisted of monthly sampling, however some lakes had occasion higher sampling frequency. Where multiple data were collected from a single site in a single month, then this data was averaged to provide a single data value per month. This was done to avoid the risk of periods of higher sample frequency causing a seasonal bias in the dataset.
- Lake Rotorua and Lake Rotoiti each have two sample sites from the main body of the lake; the monthly data from multiple sites was average to yield a single dataset for each lake (i.e. averaging

of data from Rotoiti 3 and Rotoiti 4, and averaging of data from Rotorua 2 and Rotorua 5). Past analysis has found the sites of Lake Rotorua have very similar TLI results, while for Lake Rotoiti, site 4 has lower TLI than site 3, but they follow a very similar pattern (Hamill and Scholes 2016).

2.4 Changes in analytical methods

The laboratory methods used for analysing nutrient concentrations have changed for some variables, and particularly over the period 2008 and 2009. The laboratory method changes for TN, TP and DRP that occurred between August 2008 and November 2009 resulted in significantly lower detection limits and much less variability of results (**Appendix A**), which improves the ability to detect trends and the accuracy of assessing trophic state of the oligotrophic lakes. However, the laboratory changes also resulted in a step change <u>decrease</u> in TN results and a step change <u>increase</u> in TP; this complicated the assessment of water quality trends and caused uncertainty when reporting state. By good fortune, these changes in TN and TP mostly cancelled each other out and consequently had little impact on the TLI score, but it did have a strong effect on other analysis like calculation of TN:TP ratios.

Investigations found that phosphorus results of samples from Rotorua lakes during the period August 2010 to October 2019 were elevated due to interference of the analysis by silica and arsenic. To address this issue, a new BOPRC laboratory method was trialled from early October 2018 and adopted in October 2019. This allowed the development of lake-specific corrections factors, and these can be used to correct the lake data during the period August 2010 to October 2019. These correction factors are described in **Appendix B**.

2.5 Detection limits and data censoring

Changes in analytical procedures during the course of the monitoring programme also resulted in changes in detection limits at different times (**Appendix A**).

Measurements that are less than the laboratory detection limit are currently recorded as uncensored values. Using uncensored data allows for more accurate trend analysis even though the individual measurements may have low accuracy when they are below the detection limit. There have been periods in the past when water quality has been censored. For the variables TN and TP the majority of censored values were recorded over the period September 2008 to October 2009 (inclusive). Since November 2009 the detection limit for TN and TP was 1 ppb, and prior to August 2008 the laboratory method was not as sensitive but actual results were usually recorded which reduced bias from censoring data.

Changes in the detection limit can result in anomalous trends in oligotrophic lakes where measurements are close to detection limits, for example, Lake Rotomā, Ōkataina and Tarawera. Hamill and Scholes (2016) tested the influence of changes in detection limit by repeating trend analysis for TN and TP on a modified dataset where the minimum value was set at the highest detection limit over the period. The results of the trend analysis were similar to that of the unmodified dataset. Censored data was not adjusted for the analyses undertaken in this report.

2.6 Water quality state assessment

2.6.1 Trophic Level Index

The trophic state of each lake was assessed using the Trophic Level Index (**TLI**) (Burns et al. 2000). The TLI integrates four key measures of lake trophic state - TN, TP, Chl-*a* and Secchi depth. 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 (**Table 2.2**).

***Table 2.2**: Definition of Trophic Levels based on water quality measures (source Burns et al. 2000)*

Trophic State	TLI Score	Chl-*a* (mg/m^3)	Secchi depth (m)	TP (mg/m^3)	TN (mg/m^3)
Ultra-microtrophic	<1	< 0.33	> 25	< 1.8	< 34
Microtrophic	1 - 2	0.33 – 0.82	15 - 25	1.8 – 4.1	34 - 73
Oligotrophic	2 - 3	0.82 - 2.0	15 - 7.0	4.1 – 9.0	73 - 157
Mesotrophic	3 - 4	2.0 - 5.0	7.0 - 2.8	9.0 - 20	157 - 337
Eutrophic	4 - 5	5.0 - 12	2.8 - 1.1	20 – 43	337 - 725
Supertrophic	5 - 6	12-31	1.1 - 0.4	43-96	725 - 1,558
Hypertrophic	>6	>31	<0.4	>96	>1,558

For reporting water quality state, the TLI was calculated using annual average values of TN, TP, Secchi depth and chl-*a* from the integrated top /epilimnion water samples (Burns et al. 2000). The results were reported as an annual average and a three-year average. For trend analysis the TLI was calculated for each individual sample occasion to allow the use of the seasonal Kendal statistical method.

In this report, the TLI was calculated using the following regression equations from the Lake Watch software:

$$TL\text{-}n = -3.61+3.01 \log(TN)$$

$$TL\text{-}p = 0.218+2.92 \log(TP)$$

$$TL\text{-}s = 5.56+2.6 \log(1/SD - 1/40)$$

$$TL\text{-}c = 2.22+2.54 \log(Chl\ a)$$

$$TLI = (TL\text{-}n + TL\text{-}p + TL\text{-}s + TL\text{-}c)/4$$

where:

TN = total nitrogen (mg/m^3)

TP = total phosphorus (mg/m^3)

SD = Secchi depth (m)

Chl-*a* = chlorophyll-*a* (mg/m^3)

Note that three different formulas can be used for calculating **TL-s**. This report uses the formula that is incorporated into the BOPRC Lake Watch software. This provides consistency with past calculations of TLI by BOPRC. It also produces very similar results to the formula provided in Burns et al. (2000). The influence of the different formula for TL-s is discussed in **Appendix C**.

The TLI for Lake Rotokakahi outlet was calculated as TLI3 (the average of TN-n, TL-p and TL-c). TL-s was excluded because water clarity from this site is measured as black disc rather than Secchi depth.

2.6.2 National Policy Statement for Freshwater Management (NPS-FM)

The National Policy Statement for Freshwater Management (**NPS-FM**) (MfE 2020) includes a National Objectives Framework (NOF) which outlines several compulsory national values, including 'ecosystem health'. Appendix 2a of the NPS-FM sets water quality attributes that contribute to these values and that require limits on resource use. Numerical thresholds define environmental quality bands for each attribute, including minimum acceptable states called 'national bottom-lines' (generally define by the C/D band threshold). The numeric attributes applicable to lake ecosystem health include: phytoplankton biomass, TN, TP and NH4-N toxicity (**Table 2.3**). Appendix 2B lists additional attributes require action plans if the target freshwater attribute state is not met. For lake ecosystem health these include: submerged plants Native Condition Index, submerged plants Invasive Impact Index, lake-bottom DO, and mid-hypolimnetic DO.

This report records the NPS-FM lake attributes associated with trophic state (Chl-a, TN and TP)[1] along-side that of TLI for comparative purposes.

***Table 2.3**: Values used to define band thresholds for NPS-FM attributes relevant to lake ecosystem health. Numbers in bold are the 'bottom-line' values. All values in mg/m^3.*

			NPS-FM Grade			
Variable	**Stat.**	**Lake type**	**A**	**B**	**C**	**D**
Chl-*a*	max	all	≤10	25	**60**	>60
Chl-*a*	median	all	≤2	5	**12**	>12
TP	median	all	≤10	20	**50**	>50
TN	median	stratified	≤160	350	**750**	>750
TN	median	polymictic	≤300	500	**800**	>800
NH4-N	median	all	≤30	**240**	1300	>1300
NH4-N	max	all	≤50	**400**	2200	>2200

NH4-N numeric values based on pH8 and temperature of 20^{o}C

[1] Table 1, Table 3, and Table 4, respectively of the NPS-FM (2020).

2.7 Trend analysis

2.7.1 Trend analysis method

Water quality trends were analysed for the periods January 1991 to December 2021 (31 years), January 2001 to December 2021 (21 years) and January 2010 to December 2021 (12 years). In some lakes there was insufficient data to have a full 31-year record period, and in these cases the longest full record was used. These time periods were chosen because most lakes had monitoring data extending to 1991, consistent monthly monitoring of all Rotorua lakes began between 2001 and 2002, and data since 2010 is less influenced by the changes of analytical method for TN and TP.

The trends were statistically determined using a seasonal Kendall trend test routine. The trend test procedures were performed using the TimeTrends v8.0 software package (Jowett, 2018) and allowed for directional confidence testing as recommended by McBride et al (2014). Tests were performed using monthly 'seasons' (period 12-year period and 21-year period) or quarterly seasons and using all values per season. Quarterly seasons was used for the longer duration because most lakes did not have regular monthly sampling prior to 2000.

The Seasonal Kendall test, is a commonly used non-parametric methods of detecting trends statistically (Helsel and Hirsch 1992). Two results were produced, a slope analysis based on confidence limits and a Kendall statistic P-value. The slope analysis is a non-parametric test that calculated the median of all possible inter-observation slopes. The Sen slope for each test was normalised by dividing by the raw data median to give the *relative* Sen (**RSEN**) and this was expressed as the Percent Annual Change (**PAC**). Confidence limits were used to assess the likelihood of a positive (or negative) slope. If the sign of both the upper and lower confidence limits on the slope are the same (or one limit is zero), then we can infer that there is a trend at the confidence limit (McBride 2019).

The Kendall test P-value was used to assess the confidence in the direction of a trend. The lower the P-value the more likely it is that the trend is real (not due to chance), and the larger the PAC the larger the magnitude of the trend.

If a confidence interval of the slope analysis does not contain zero, then the trend direction (either positive of negative) is "established with confidence". If it does contain zero, then the trend has insufficient data to confidently determine direction and is "indeterminant" (Larned et al 2016).

2.7.1 Trend interpretation

Rather than just accept a P-value to define statistical significance (e.g. P-value <0.05), the likelihood that the trend has a given direction was expressed in a more nuanced way using probabilities. Trends are declared to be "confidently" detected when direction is established with 95% certainty. However, the direction can be determined with lower levels of confidence and expressed in terms of "likelihood". The likelihood of a water quality trend was expressed using categories in **Table 2.5** (consistent with Stocker et al 2014, Snelder et al. 2018). The direction of trend (increasing or decreasing) was determined from the sign of the Sen slope / PAC.

The slope analysis based on confidence limits (Sen Probability) and the Kendall test (P-value) are usually similar, however they can give different results when many tied values or censored values are present in the data. Even though a "very likely" trend or higher may be detected, the trend may not be environmentally important. Where the Kendall Statistic and slope analysis provided different results, then the trend was assessed as ''uncertain' (also called indeterminant). This avoided the need of using an arbitrary threshold for PAC (e.g. of >1%) to assess "*practically important*" trends as used previously (e.g. Scarsbrook 2006, Ballantine et al. 2010).

Summary tables used in this report show the trend confidence as "very likely", "likely" and "uncertain/unlikely" as described in **Table 2.4** below. The tables use arrows to indicate the trend confidence and direction as follows: "very likely increasing" ↑ , "likely increasing" ↗, "uncertain" → , "likely decreasing" ↘, and "very likely decreasing" ↓. Lakes that show a step change in TN in late 2009 are identified.

Table 2.4*: Confidence categories used to express the probability of a trend in water quality (from Time Trends and consistent with Stocker et al., 2014, Snelder and Fraser 2018)*

Likelihood summary	Likelihood (TimeTrends)	Kendall P-value	Confidence limits (%)	Slope Direction Likelihood
Very Likely	Virtually certain	≤0.01	99	≥0.995
	Very likely	≤0.05	95	≥0.975
Likely	Likely	≤0.1	90	≥0.95
	Possible	0.33	0.67	≥0.835
Uncertain / Unlikely	About as likely as not	≤0.67	33	≥0.665
	Unlikely	≤0.9	10	≥0.55
	Extremely unlikely	≤0.95	5	≥0.525
	Exceptionally unlikely	0.99	1	≥0.505

2.7.1 Exclusion of series

The trend method is not affected by the occasional missing data and to censored data (Hirsch and Slack 1984), but it is good practice in trend analysis to exclude time-series that offer insufficient temporal span or frequency of detection (e.g., Helsel and Hirsch, 1992). Prior to trend analysis the dataset was filtered to restrict site-variable combinations to those for which less than 15% of data was missing (Snelder 2018). This excluded clarity measurements from Rotokakahi outlet for which TLI3 was used rather than TLI4.

Trends are most robust when there are few censored values in the time-period of analysis. Helsel (1990) estimated that the impact of censored values on the Sen slope is negligible when fewer than 15% of the values are censored. The dataset did not identify censored values. Runs of tied values were apparent in TP data for some lakes (Lake Ōkāreka, Ōkataina, Rotomā, and Tikitapu), and consequently the TP trends in these lakes need to be treated with caution.

2.8 Correlation analysis

The inter-annual variability of TLI values was examined by comparing the variability between lakes and comparing the variability with climatic variables. Annual data (rolling 12-month mean) was used to de-seasonalise the data set. Correlations between variables were assessed using spearman-rank correlation, this is a non-parametric test that is not sensitive to assumptions about data distribution.

The inter-annual variability of TLI for each lake was compared with the following climatic variables, which were all annualised using a 12-month rolling mean for the purpose of analysis:

- Total rainfall monthly (Rotorua at Whakarewarewa site, from The National Climate Database, NIWA).
- Mean wind monthly (Rotorua Airport WS site from The MetService site)
- Total sunshine hours, monthly (Rotorua Aero, Rotorua Ews, Taurana Aero sites from The National Climate Database, NIWA)
- Lake Rotomā water level as a proxy for groundwater (source BOPRC), and
- The Southern Oscillation Index (**SOI**) (monthly rolling average) (source: https://www.stats.govt.nz/indicators/el-nino-southern-oscillation).

3. Lake state and trends in TLI

3.1 Current State of Te Arawa Lakes

3.1.1 TLI compared to Targets

This section provides and update of the TLI scores for each of the Rotorua Te Arawa lakes and compares it with the TLI targets set in Objective 11 of the RNRP. Method 41 of the RNRP of the RNRP triggers action plans for lakes when the three-year moving average TLI exceeds the lake's target TLI by 0.2 TLI units for two consecutive years. To assess this condition **Table 3.1** shows three-year mean TLI for the years ending July 2020 and July 2021 in addition to the annual TLI results.

Eight lakes exceed their TLI targets for the 3-year period ending July 2021 (plus Rotoiti at Okawa Bay). However only four lakes currently exceed the requirements in the RNRP for setting action plans, namely: Lakes Rotoehu, Rotoiti, Rotokakahi, and Tikitapu.

Annual TLI and its components is shown in **Table 3.2** for the previous five years. This allows for a more details understanding of changes in annual change TLI over recent years and which TLI component is driving higher or lower TLI values. For example, in Lake Rotorua over the last five years, the annual TLI met the target value of 4.2, but chlorophyll-*a* concentrations were indicative of considerably higher TLI, while TN and TP were lower.

Table 3.1: Lake TLI compared to targets for July 2020-2021 and the 3-year periods ending July 2020 and July 2021. Red shaded cells do not meet the TLI target, bolded numbers exceed the Target by more than 0.2 TLI units.

Lake	TLI Target	TLI 2021	TLI 3-yr mean 2019-21	TLI 3-yr mean 2018-20	Trophic state	Mean (July 2019 - July 2021) TN (µg/L)	TP (µg/L)	Chl-*a* (µg/L)	Secchi (m)
Ōkāreka	3.0	3.1	3.1	**3.2**	mesotrophic	180	7.9	3.1	7.8
Ōkaro	5.0	4.4	4.6	4.9	eutrophic	624	43.1	11.9	4.1
Ōkataina	2.6	2.7	2.6	2.7	oligotrophic	99	6.5	1.9	10.4
Rerewhakaaitu	3.6	3.3	3.7	**3.9**	mesotrophic	377	10.5	4.9	5.4
Rotoehu	3.9	4.3	**4.7**	**4.8**	eutrophic	485	37.2	17.1	2.4
Rotoiti	3.5	3.7	**3.7**	**3.7**	mesotrophic	176	23.1	5.7	6.1
Rotoiti Okawa Bay		4.7	4.5	4.4	eutrophic	367	40.6	11.1	3.2
Rotokakahi Outlet	3.1	3.4	**3.5**	**3.6**	mesotrophic	212	13.1	3.8	4.8 *
Rotomā	2.3	2.3	2.4	2.4	oligotrophic	115	4.6	1.2	12.0
Rotomahana	3.9	3.5	3.6	3.8	mesotrophic	207	22.2	3.4	5.4
Rotorua	4.2	4.4	4.2	4.2	eutrophic	310	20.7	10.9	3.1
Tarawera	2.6	2.7	2.7	2.8	oligotrophic	89	9.5	1.5	8.7
Tikitapu	2.7	3.2	**3.0**	**2.9**	oligotrophic	179	4.7	2.5	5.8

TLI target from the Regional Water & Land Plan
Rotokakahi was samped at outlet (Te Wairoa Stream) to calculate TLI3. Secchi est. from black disc.

Table 3.2: Annual average for TLI and components for each Te Arawa Lake. Five-year averages are shown in bold and the TLI target shown brackets.

Lake / year	TLI	TL-c	TL-s	TL-n	TL-p
Ōkāreka (3.0)	**3.2**	**3.7**	**3.1**	**3.2**	**3.0**
30/6/2017	3.4	3.8	3.2	3.4	3.1
30/6/2018	3.5	4.2	3.2	3.2	3.2
30/6/2019	3.3	3.8	3.1	3.2	2.9
30/6/2020	2.9	3.1	2.9	3.1	2.7
30/06/2021	3.1	3.5	3.0	3.2	2.9
Ōkaro (5.0)	**4.8**	**5.2**	**4.1**	**4.9**	**5.0**
30/6/2017	4.9	5.6	4.2	5.1	4.8
30/6/2018	5.2	6.0	4.5	5.1	5.3
30/6/2019	5.0	5.5	4.1	5.1	5.3
30/6/2020	4.4	4.5	3.7	4.7	4.9
30/6/2021	4.4	4.6	3.8	4.6	4.7
Ōkataina (2.6)	**2.7**	**3.1**	**2.6**	**2.3**	**2.6**
30/6/2017	2.6	3.1	2.5	2.2	2.5
30/6/2018	2.8	3.5	2.7	2.2	2.8
30/6/2019	2.6	3.0	2.7	2.3	2.5
30/6/2020	2.6	2.9	2.6	2.3	2.6
30/6/2021	2.7	2.9	2.5	2.5	2.7
Rerewhakaaitu (3.6)	**3.7**	**3.9**	**3.5**	**4.1**	**3.2**
30/6/2017	3.5	3.7	3.3	3.9	3.1
30/6/2018	4.0	4.3	3.8	4.3	3.6
30/6/2019	4.1	4.6	3.9	4.4	3.6
30/6/2020	3.5	3.5	3.4	4.1	3.1
30/6/2021	3.3	3.4	3.3	3.9	2.8
Rotoehu (3.9)	**4.7**	**5.2**	**4.5**	**4.4**	**4.6**
30/6/2017	4.5	5.0	4.5	4.4	4.2
30/6/2018	4.7	5.2	4.5	4.3	4.9
30/6/2019	5.3	6.0	4.9	5.0	5.4
30/6/2020	4.5	4.9	4.4	4.3	4.4
30/6/2021	4.3	4.6	4.3	3.9	4.3
Rotoiti (3.5)	**3.7**	**4.2**	**3.4**	**3.1**	**4.2**
30/6/2017	3.8	4.1	3.4	3.2	4.4
30/6/2018	3.8	4.4	3.6	3.1	4.2
30/6/2019	3.7	4.4	3.4	3.2	4.0
30/6/2020	3.7	3.9	3.3	3.1	4.3
30/6/2021	3.7	4.0	3.3	3.2	4.3
Rotoiti Okawa Bay	**4.5**	**4.7**	**4.3**	**4.0**	**4.9**
30/6/2017	4.4	4.5	4.4	3.9	4.9
30/6/2018	4.4	4.7	4.5	3.8	4.8
30/6/2019	4.6	5.0	4.3	4.1	4.9
30/6/2020	4.2	4.1	4.1	3.9	4.6
30/6/2021	4.7	5.2	4.1	4.3	5.1

Lake / year	TLI	TL-c	TL-s	TL-n	TL-p
Rotokakahi (3.1)	**3.6**	**3.8**	**3.7**	**3.4**	**3.5**
30/6/2017	3.7	4.0	3.7	3.6	3.5
30/6/2018	3.6	4.0	3.7	3.3	3.5
30/6/2019	3.7	4.0	3.7	3.5	3.6
30/6/2020	3.4	3.5	3.5	3.4	3.5
30/6/2021	3.4	3.7	3.7	3.3	3.3
Rotomā (2.3)	**2.3**	**2.3**	**2.3**	**2.5**	**2.1**
30/6/2017	2.1	2.1	2.1	2.5	1.7
30/6/2018	2.4	2.6	2.4	2.4	2.1
30/6/2019	2.4	2.4	2.6	2.6	2.2
30/6/2020	2.3	2.2	2.2	2.6	2.3
30/6/2021	2.3	2.5	2.3	2.5	2.0
Rotomahana (3.9)	**3.7**	**3.8**	**3.6**	**3.3**	**4.2**
30/6/2017	3.8	3.8	3.5	3.3	4.4
30/6/2018	4.0	4.4	3.8	3.4	4.3
30/6/2019	3.8	3.8	3.5	3.5	4.3
30/6/2020	3.6	3.5	3.6	3.4	4.1
30/6/2021	3.5	3.3	3.4	3.2	4.0
Rotorua (4.2)	**4.2**	**4.8**	**4.2**	**4.0**	**3.9**
30/6/2017	4.1	4.5	4.1	4.1	3.6
30/6/2018	4.2	5.0	4.2	3.9	3.7
30/6/2019	4.3	5.0	4.3	3.9	3.9
30/6/2020	4.0	4.5	4.0	3.8	3.8
30/6/2021	4.4	5.0	4.3	3.9	4.4
Tarawera (2.6)	**2.8**	**2.7**	**2.9**	**2.3**	**3.2**
30/6/2017	2.9	2.7	2.8	2.4	3.7
30/6/2018	2.9	3.0	2.9	2.2	3.4
30/6/2019	2.8	2.7	3.0	2.3	3.2
30/6/2020	2.6	2.6	2.9	2.2	2.9
30/6/2021	2.7	2.6	2.7	2.3	3.1
Tikitapu (2.7)	**2.9**	**3.1**	**3.2**	**3.1**	**2.3**
30/6/2017	2.7	2.7	2.7	3.1	2.2
30/6/2018	3.0	3.4	3.0	3.1	2.5
30/6/2019	3.0	3.4	3.3	3.2	2.2
30/6/2020	2.8	2.9	3.1	3.1	2.0
30/6/2021	3.2	3.3	3.8	3.3	2.3

3.1.2 NPS-FM

The NPS-FM lake attributes for TN, TP and Chl-a were assessed for the three-year period ending July 2021. Consistent with NPS-FM grading rules for lake trophic state, the Rotorua Te Arawa lakes were graded based on the worst scoring attribute (**Table 3.3**). Two lakes were in the "D" band (Ōkaro and Rotoehu) which is below the bottom-line. These lakes were graded "D" because of their high maximum chlorophyll-*a* values (>60 mg/m³) - indicative of algae blooms.

The trophic state attribute bands of A, B, C and D approximately correspond to oligotrophic (or better), mesotrophic, eutrophic and supertrophic (or worse), respectively. However, the grading of lake trophic state using the NPS-FM attributes tends to be more stringent than the TLI because the TLI is calculated as an average of scores derived from TN, TP, Chl-*a* and Secchi depth, while the NPS-FM attributes can fail a bottom-line for any individual variable of TN, TP or Chl-*a*. Also, the NPS-FM maximum statistic for Chl-*a*, sets bands based on individual algal blooms, as opposed to high concentrations occurring on average.

Notwithstanding the differences between grading lake water quality using the TLI compared to the NPS-FM attributes, it is noteworthy that Lake Ōkaro fails the NPS-FM grade but is still within its TLI target. This raises the question of whether the TLI target set for Lake Okaro is too lenient, as it is not ensuring am acceptable state as set by the NPS-FM.

Table 3.3: Comparison of lake water quality with NPS-FM bottom-line values (3-year period 2018/19 to 2020/21). Colours indicate the NPS-FM grading.

		NPS-FM bottom line				2018/19 - 2020/21				
		max	median (mg/m³)			max	median (mg/m³)			NPS-FM
Lake	mixing	Chl-*a*	Chl-*a*	TN	TP	Chl-*a*	Chl-*a*	TN	TP	Grade
Ōkāreka	stratified	60	12	750	50	10.5	2.4	182	7.8	B
Ōkaro	stratified	60	12	750	50	68.5	9.0	559	30.6	D
Ōkataina	stratified	60	12	750	50	7.4	2.2	86	7.0	B
Rerewhakaaitu	polymictic	60	12	800	50	14.2	3.5	360	9.4	B
Rotoehu	polymictic	60	12	800	50	96.4	11.5	334	31.1	D
Rotoiti	stratified	60	12	750	50	19.1	5.1	173	20.5	C
Rotoiti Okawa Bay	polymictic	60	12	800	50	35.9	10.1	327	36.2	C
Rotokakahi Outlet	stratified	60	12	750	50	11.8	2.8	205	12.0	B
Rotomā	stratified	60	12	750	50	2.4	1.2	113	4.2	A
Rotomahana	stratified	60	12	750	50	16.4	2.5	203	22.0	C
Rotorua	polymictic	60	12	800	50	21.2	11.7	314	17.0	C
Tarawera	stratified	60	12	750	50	3.6	1.2	90	8.9	A
Tikitapu	stratified	60	12	750	50	8.4	2.0	173	5.0	B

Rerewhakaaitu, Rotoehu, Okawa Bay and Rotorua stratify for only short periods of time.
Rotokakahi based on sampling of outlet (Te Wairoa Stream)

3.2 Statistical trends

TLI trends and those of its component parts of TL-n, TL-p, TL-c and TL-s were calculated for each of the Rotorua Te Arawa lakes. The confidence and direction of trends were determined for three time periods (1991 - 2021, 2001 - 2021 and 2010 - 2021)[2]. For trends identified as “very likely” (Sen slope P-value ≤0.05), the 31-year and the 21-year periods both had seven lakes with decreasing (improving) TLI and one lake with increasing (worsening) TLI; the most recent 12-year period (2010-2021) indicated two lakes had decreasing (improving) TLI and three lakes had increasing (worsening) TLI (**Table 3.4**).

In many lakes the decreasing (improving) trends in TLI over the longer time periods (31-years and 21-years) appeared to be driven by decreasing trends in TN, which was often apparent as a step change decrease in TN in around 2009, that coincided with the change in laboratory method (discussed in **Appendix B**). All 13 lakes had “very likely” decreasing TN over the 31-year and 21-year period, but only four lakes had decreasing TN over the recent 12-year period. Lakes that had a “very likely” decrease in each of the TLI variables (TL-n, TL-p, TL-c, TL-s) over longer periods were: Ōkaro, Ōkataina, and Rotorua (**Table 3.5, Figure 3.1**). A change in Chl-*a* and Secchi depth is particularly meaningful because these are observable by the public.

Lake Rerewhakaaitu was the only lake with increasing (worsening) TLI over the longer durations, which appears to be driven by an increase in concentrations of TP and Chl-*a* (**Table 3.5**). Over the last 32 years there have frequently been periods when the lake has exceeded its TLI target of 3.6 (1995/96 to 1999/00, 2007/08 to 2011/12, 2017/18 to 2019/20) (**Figure 3.1**).

For, the 12-year period, the three lakes with very likely increasing (worsening) TLI were Lakes Rotoehu, Rotoiti Okawa Bay and Rotomā. For these lake sites, worsening trends were apparent with “likely” or “very likely” confidence for all four TLI variables (TN, TP, Chl-*a* and Secchi), which gives added confidence in the reliability of the trend. However, the 12-year period could still be influenced by climatic variability.

A cumulative sum (CUSUM) analysis was undertaken to identify step changes in the time series data, which appear as changes in the slope of the CUSUM graph. The graphs were standardised by dividing by the standard error so that the range of the scale indicates the statistical significance of the difference between the highest and lowest CUSUM. A range > 10 indicates a probable statistically significant change. A straight line indicates no trend, an abrupt change in slope indicates a step change, an upward slope (A-shape) indicates an increasing trend, and a downward slope (U-shape) a decreasing trend. The analysis indicates a period around about 2009 to variably 2018 / 2022 during which the TLI in many lakes decreased (i.e. improved) (Ōkaro, Ōkataina, Rotorua, Rotoehu, Rotoiti, Rotomā, Rotorua, Tikitapu) (**Appendix E**).

Standardised CUMSUM graphs for each component of the TLI (TL-n, TL-p, TP-c, and TL-s) are also in **Appendix E**. These graphs illustrate the change decline in TN that occurred in many lakes around 2009, while for other variables such as Chl-a, a switch towards decreasing concentrations occurred around 2012.

[2] These time periods reflect improving data availability and quality. Regular data monitoring of most lakes is available since 1991, but consistent monthly sampling is available since 2001. The possible effects of analytical changes in TN and TP are minimised by analysing data since 2010

***Table 3.4**: Summary of TLI trend direction, statistical confidence and percent annual change (PAC) for Te Arawa lakes. Arrows indicate the trend confidence and direction as follows: "very likely increasing" ↑ , "likely increasing" ↗, "uncertain" → , "likely decreasing" ↘, and "very likely decreasing" ↓. Lakes that show a step change in TN in late 2009 are identified.*

Lake	1991 - 2021 incl.		2001 - 2021 incl.		2010 - 2021 incl.		TN ⇓
	Trend	PAC	Trend	PAC	Trend	PAC	2009/10
Ōkāreka	→	0.0	→	0.1	→	0.0	Y
Ōkaro	↓	-0.8	↓	-0.9	↘	-0.6	
Ōkataina	↓	-0.5	↓	-0.6	→	-0.1	Y
Rerewhakaaitu	↑	0.2	↑	0.2	↓	-0.7	
Rotoehu	↓	-0.3	↓	-0.2	↑	1.4	
Rotoiti	↓	-0.2	↓	-0.5	↗	0.3	Y
Rotoiti Okawa Bay	↘	-0.2	↘	-0.2	↑	1.0	
Rotokakahi Outlet	→	0.0	→	-0.1	↓	-0.8	
Rotomā	↓	-0.3	↓	-0.3	↑	1.4	Y
Rotomahana	↓	-0.2	↓	-0.3	↘	-0.3	
Rotorua	↓	-0.5	↓	-1.0	→	0.0	Y
Tarawera	→	0.0	↘	-0.1	→	-0.1	Y
Tikitapu	↘	-0.1	↘	-0.2	↗	0.3	Y

***Table 3.5**: Trend direction, statistical confidence and percent annual change (PAC) in the TLI for time periods of c. 31-years, 21-years, and 12-years. Arrows indicate the trend confidence and direction as follows: "very likely increasing" ↑ , "likely increasing" ↗, "uncertain" → , "likely decreasing" ↘, and "very likely decreasing" ↓.*

***ca.* 31-year period, 1991-2021 inclusive**

	TLI		TL-n		TL-p		TL-c		TL-s	
Lake	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**
Ōkāreka	→	0.0	↓	-0.4	↑	0.7	↓	-0.4	↑	0.3
Ōkaro	↓	-0.8	↓	-0.6	↓	-1.1	↓	-0.8	↓	-0.7
Ōkataina	↓	-0.5	↓	-1.2	↘	-0.2	↓	-0.4	↓	-0.2
Rerewhakaaitu	↑	0.2	↓	-0.2	↑	0.8	↑	0.3	→	0.0
Rotoehu	↓	-0.3	↓	-0.5	↘	-0.3	↘	-0.2	→	0.0
Rotoiti	↓	-0.2	↓	-0.8	↑	0.2	↓	-0.3	→	0.0
Rotoiti Okawa Bay	↘	-0.2	↓	-0.4	↑	0.2	↘	-0.4	↓	-0.3
Rotokakahi Outlet	→	0.0	↓	-0.2	→	0.1	↘	-0.2	↓	-0.7
Rotomā	↓	-0.3	↓	-0.8	→	0.0	↘	-0.3	→	0.0
Rotomahana	↓	-0.2	↓	-0.2	↘	-0.3	↘	-0.2	↓	-0.2
Rotorua	↓	-0.5	↓	-0.4	↓	-1.1	↓	-0.3	↓	-0.2
Tarawera	→	0.0	↓	-0.8	↑	0.7	↘	-0.2	↓	-0.2
Tikitapu	↘	-0.1	↓	-0.4	→	0.0	→	0.0	↘	-0.2

21-year period, 2001 - 2021 inclusive

	TLI		TL-n		TL-p		TL-c		TL-s	
Lake	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**
Ōkāreka	→	0.1	↓	-0.4	↑	0.6	↘	-0.3	↗	0.2
Ōkaro	↓	-0.9	↓	-0.6	↓	-1.2	↓	-1.0	↓	-0.9
Ōkataina	↓	-0.6	↓	-1.3	↘	-0.2	↓	-0.8	↓	-0.3
Rerewhakaaitu	↑	0.2	↓	-0.2	↑	0.7	↑	0.4	→	0.0
Rotoehu	↓	-0.2	↓	-0.3	↘	-0.3	→	0.0	→	0.0
Rotoiti	↓	-0.5	↓	-1.2	→	0.1	↓	-0.8	→	0.0
Rotoiti Okawa Bay	↘	-0.2	↓	-0.3	↑	0.2	↘	-0.4	↓	-0.3
Rotokakahi Outlet	→	-0.1	↓	-0.3	→	0.0	→	-0.2	↓	-0.8
Rotomā	↓	-0.3	↓	-0.8	→	0.0	↓	-0.3	↗	0.1
Rotomahana	↓	-0.3	↓	-0.2	↘	-0.2	↘	-0.3	↘	-0.2
Rotorua	↓	-1.0	↓	-0.7	↓	-1.6	↓	-1.2	↓	-0.5
Tarawera	↘	-0.1	↓	-0.9	↑	0.6	→	0.0	↘	-0.2
Tikitapu	↘	-0.2	↓	-0.4	→	0.0	→	0.0	↓	-0.5

12-year period, 2010 - 2021 inclusive

	TLI		TL-n		TL-p		TL-c		TL-s	
Lake	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**	**Trend**	**PAC**
Ōkāreka	→	0.0	→	-0.1	↑	0.9	→	-0.3	→	0.2
Ōkaro	↘	-0.6	↓	-0.7	↘	-0.3	↘	-0.6	↓	-1.2
Ōkataina	→	-0.1	↓	-0.4	↗	0.4	↓	-0.9	↘	-0.3
Rerewhakaaitu	↓	-0.7	↓	-0.3	↓	-0.9	→	-0.3	↓	-0.8
Rotoehu	↑	1.4	↑	1.6	↑	1.6	↑	1.6	↑	1.1
Rotoiti	↗	0.3	→	0.1	↑	0.4	→	0.0	↑	0.5
Rotoiti Okawa Bay	↑	1.0	↑	0.8	↑	0.7	↑	1.5	↗	0.5
Rotokakahi Outlet	↓	-0.8	↓	-0.4	↓	-1.1	↓	-1.0	↓	-1.1
Rotomā	↑	1.4	↑	0.5	↑	3.4	↗	0.3	↑	1.3
Rotomahana	↘	-0.3	↗	0.2	→	0.2	↓	-1.0	→	-0.2
Rotorua	→	0.0	→	0.1	↑	0.8	→	-0.3	↘	-0.2
Tarawera	→	-0.1	→	0.1	→	0.0	→	0.0	→	-0.1
Tikitapu	↗	0.3	↑	0.5	↘	0.0	↑	0.7	↗	0.5

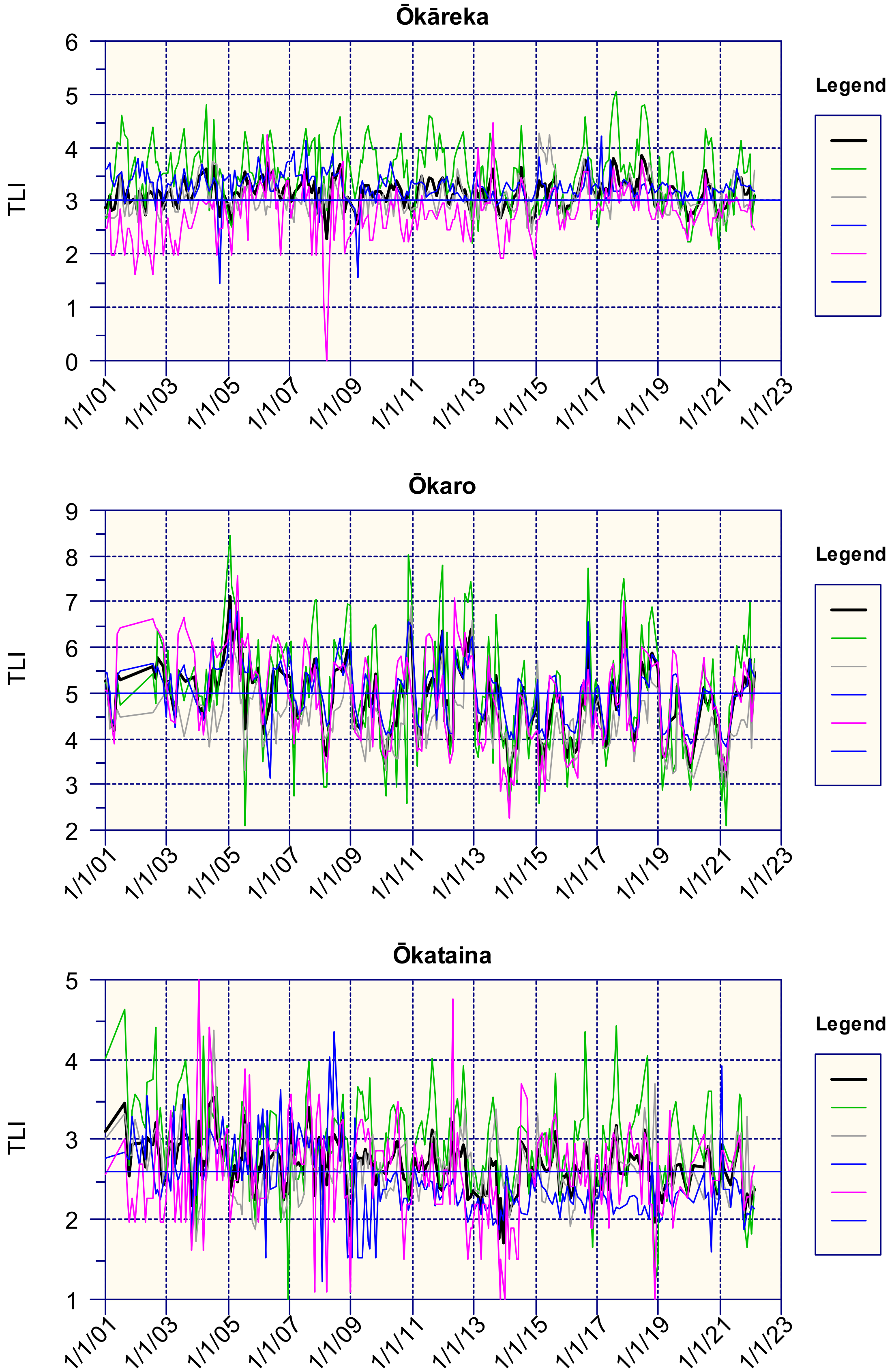


***Figure 3.1 a**: Change in monthly TLI and components (TL-c, TL-n, TL-p and TL-s) compared to target.*

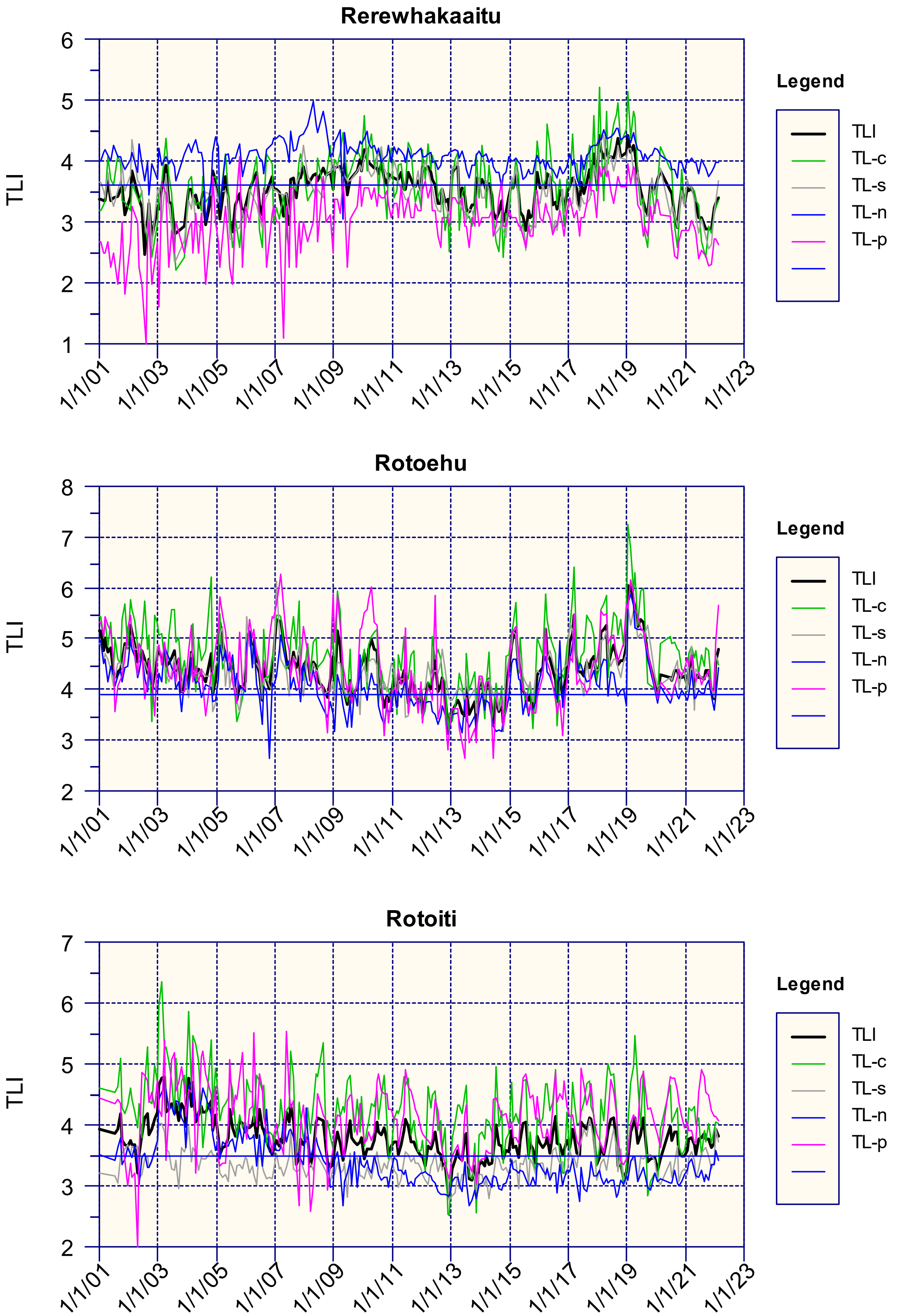


***Figure 3.1 b**: Change in monthly TLI and components (TL-c, TL-n, TL-p and TL-s) compared to target.*

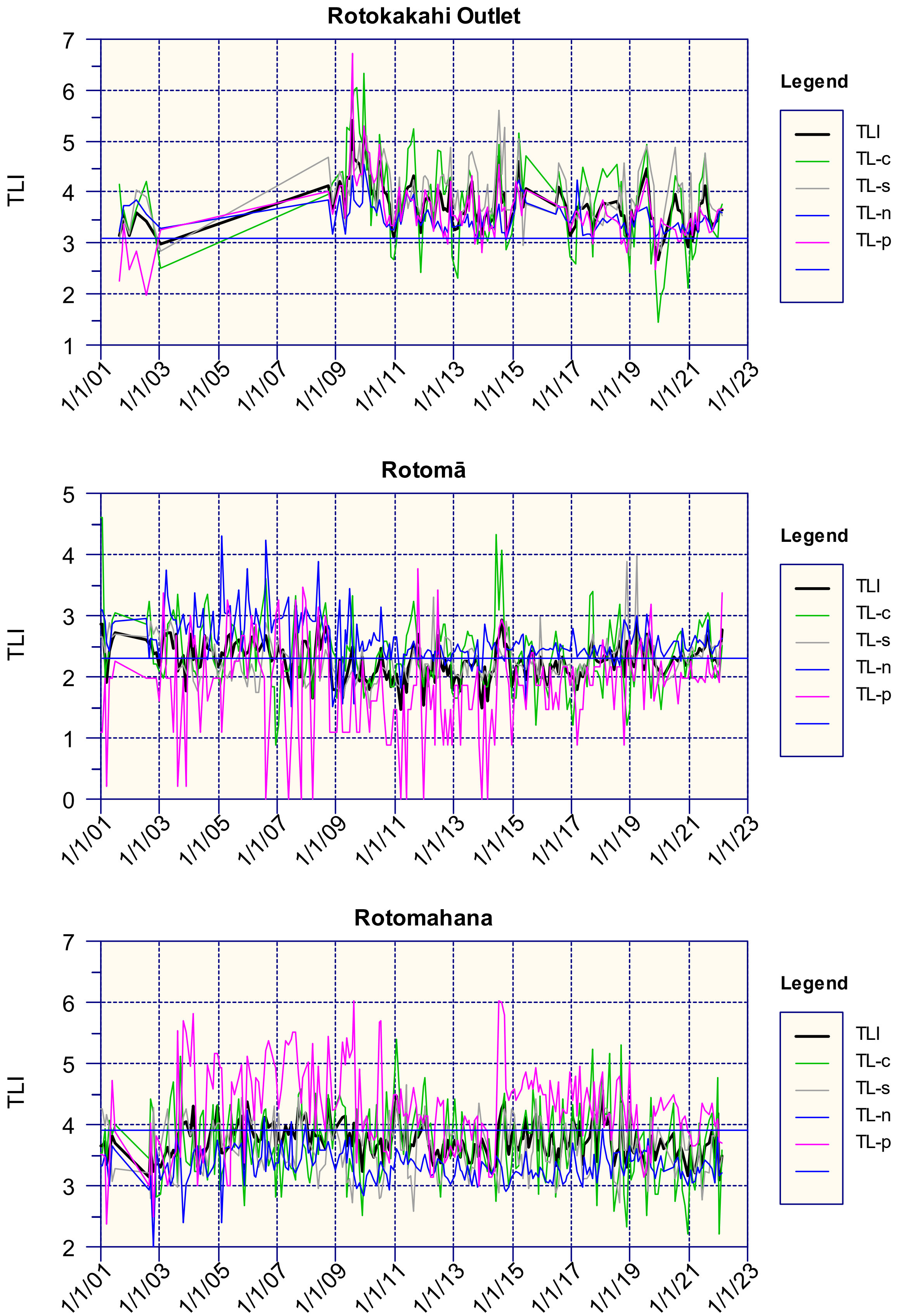


Figure 3.1 c*: Change in monthly TLI and components (TL-c, TL-n, TL-p and TL-s) compared to target.*

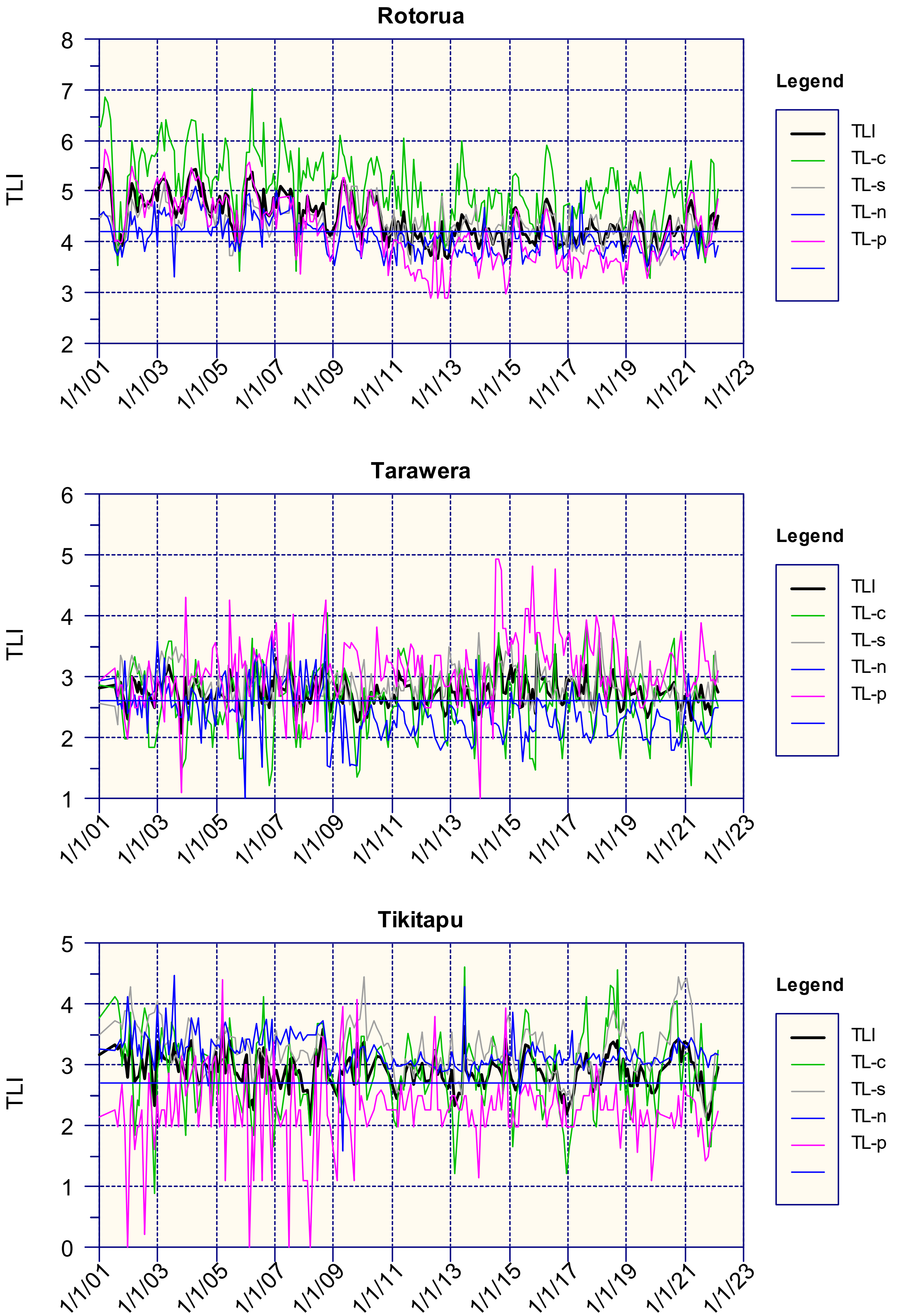


***Figure 3.1 d**: Change in monthly TLI and components (TL-c, TL-n, TL-p and TL-s) compared to target.*

3.3 Summary of TLI state and trends for each lake

A summary of the TLI state and trends for each lake is discussed below. The changes in TLI over the long term are more easily visualised by using the average annual TLI, which removes the seasonal variability; this is shown in is shown in **Figure 3.3** along with the component parts (TL-c, TL-s, TL-n, TL-p).

TLI in **Lake Ōkāreka** is just above its target and has only dropped below its target on two occasions since 1991. TL-c is typically higher, and TL-p lower, than the TLI values. Over the long term, TL-s and TL-p have increased (worsened) while TL-c and TL-n have decreased. Okāreka's lakeside community septic systems were reticulated in 2011.

The TLI in **Lake Ōkaro** has steadily decreased over time since about 2005 so that the TLI is now below its target value of 5.0. All TLI variables (TL-n, TL-p, TL-c, TL-s) have decreased (improved) together. Typically, TL-s is lower (relatively better) than the other TLI variables. Alum dosing has been used since 2003 to cap phosphorus release from the sediments.

Lake Ōkataina is oligotrophic and the TLI is currently just at its target value. TL-c tends to be higher than the TLI values. TLI values have trended downward (improved) since about 2005. TN had a substantial decline during about 2009 that was not reflected in other variables.

Lake Rerewhakaaitu is mesotrophic and currently just exceeds its TLI target. Trend analysis found that the TLI has increased since 1992, and this increasing trend is particularly apparent in TP. TL-n is relatively high compared to the TLI and TL-p– indicating possible P limitation.

Lake Rotoehu is eutrophic and substantially exceeds its TLI target. Trend analysis detected significant decreasing trends over the long term, but this may have been influenced by the large interannual variability. Management interventions to improve lake water quality include harvesting of aquatic macrophytes since 2008, alum dosing from the Soda Springs since 2011, and conversion of land to forestry.

Lake Rotoiti is mesotrophic and exceeds its TLI target. TL-c and TL-p tend to be higher than TLI values. There has been a long-term trend of decreasing TLI driven by decreasing TN and Chl-a concentrations. A step-change decrease (improvement) in TN occurred in 2009 but this was part of a trend in improving water quality. Interventions to improve lake water quality include the construction of the Okere diversion wall in 2008 and reticulation of lakeside communities (e.g. Okawa Bay 2008).

Water quality from the **Lake Rotokakahi** outlet is sampled from the Te Wairoa Stream. Clarity is measured using the black disc method, so the TLI is expressed as TLI3 using only TL-c, TL-n and TL-p. The lake (as measured at the outlet) is mesotrophic and the TLI is much higher than its target. A peak in TLI occurred in about 2010 and has since decreased.

Lake Rotomā is oligotrophic with its TLI just at its target value. Trend analysis found that the TLI has very likely improved since 1992, but this was partially driven by a step-change decrease in TN during 2009. Since 2010 the TLI has increase in Rotomā and this appears to have coincided with forestry harvesting occurring near the lake in early 2019.

Lake Rotomahana is a mesotrophic lake and its TLI is currently within its target value. The lake has large fluctuation in TP that appear to be a strong driver of the interannual variability in the TLI, but it is possible that some of this variation is due to fluctuation in silica and or arsenic interfering with past laboratory measurements (discussed in **Appendix B**).

Lake Rotorua is eutrophic with its TLI currently just at its target value. TL-c is consistently high relative to TLI values. TLI has substantially decreased (improved) in the lake since 2001 and this is reflected in improving TN, TP, Chl-a and Secchi depth clarity. Most of the improvements in water quality occurred between about 2004 and 2013, and there has been little change in more recent years. Interventions to improve lake water quality include land disposal of the city's wastewater since 1991, sewage reticulation of lakeside communities, alum dosing to lock phosphorus from Utuhina Stream (2006) and Puarenga Stream (2010), rules to cap land-based inputs.

Lake Tarawera is oligotrophic and the TLI is currently above its target value. The TLI scores have been relatively stable over time. TL-n had a statistically significant decreasing trend caused by a step-change decrease in TN during 2009 (likely related to the laboratory method change). TP has had large interannual fluctuations following a similar pattern to fluctuations seen in Rotomahana (i.e. peaks in about 2007, 2009 and 2015/16.

Lake Tikitapu is oligotrophic and the TLI is currently above its target value. The TLI has been relatively stable over time (weak evidence of improvement since about 2006), although a step-change decrease in TN occurred in about 2009. TL-p is substantially lower than the TLI and TL-n, indicating possible phosphorus limitation. The trend analysis indicated a "likely" deterioration in TLI since 2010 which should be watched to see if it continues. The lakeside campground and public amenities were reticulated in 2010.

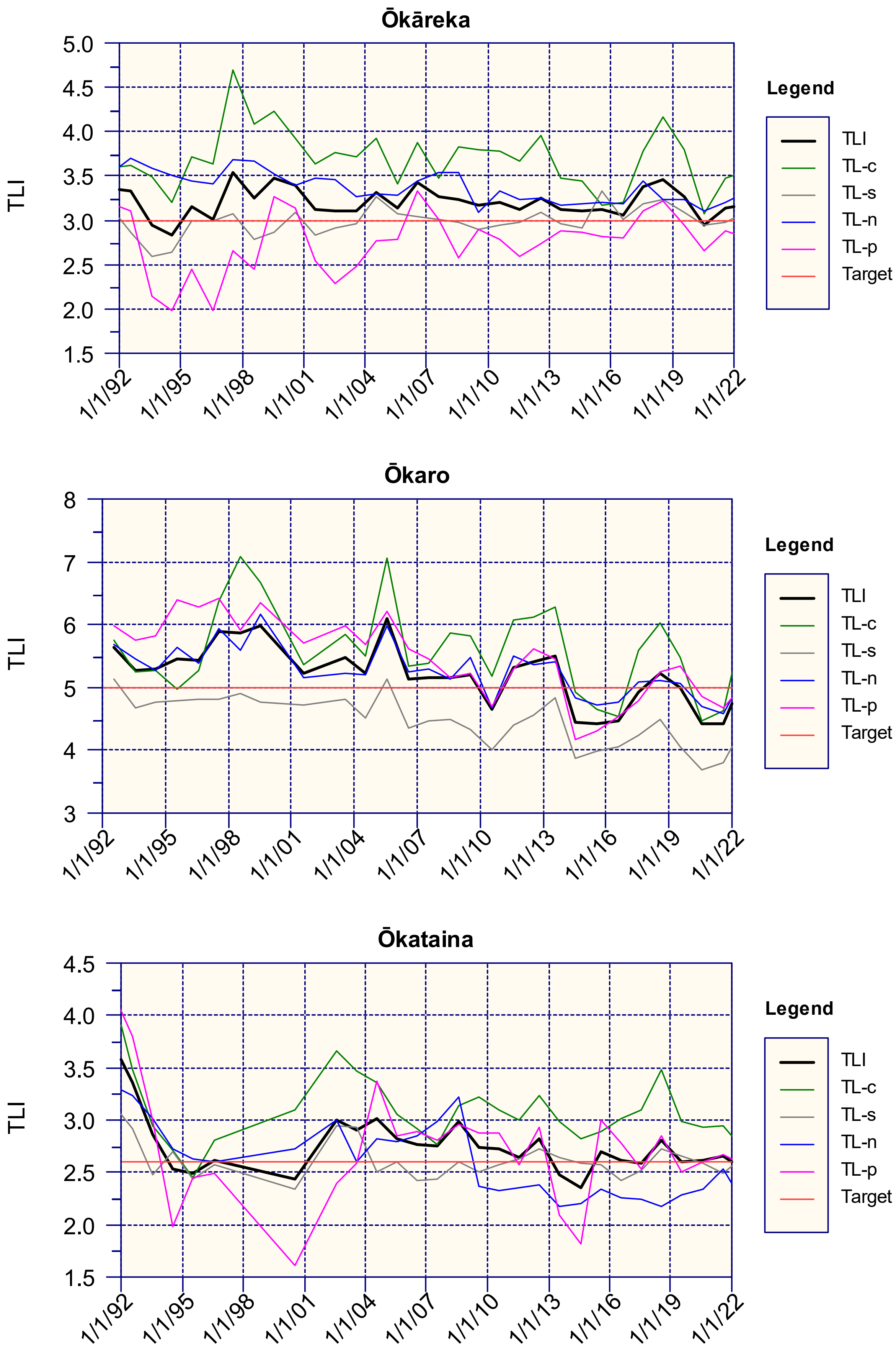


Figure 3.3 a*: Annual mean TLI and targets. Dates are the end of the hydrological year.*

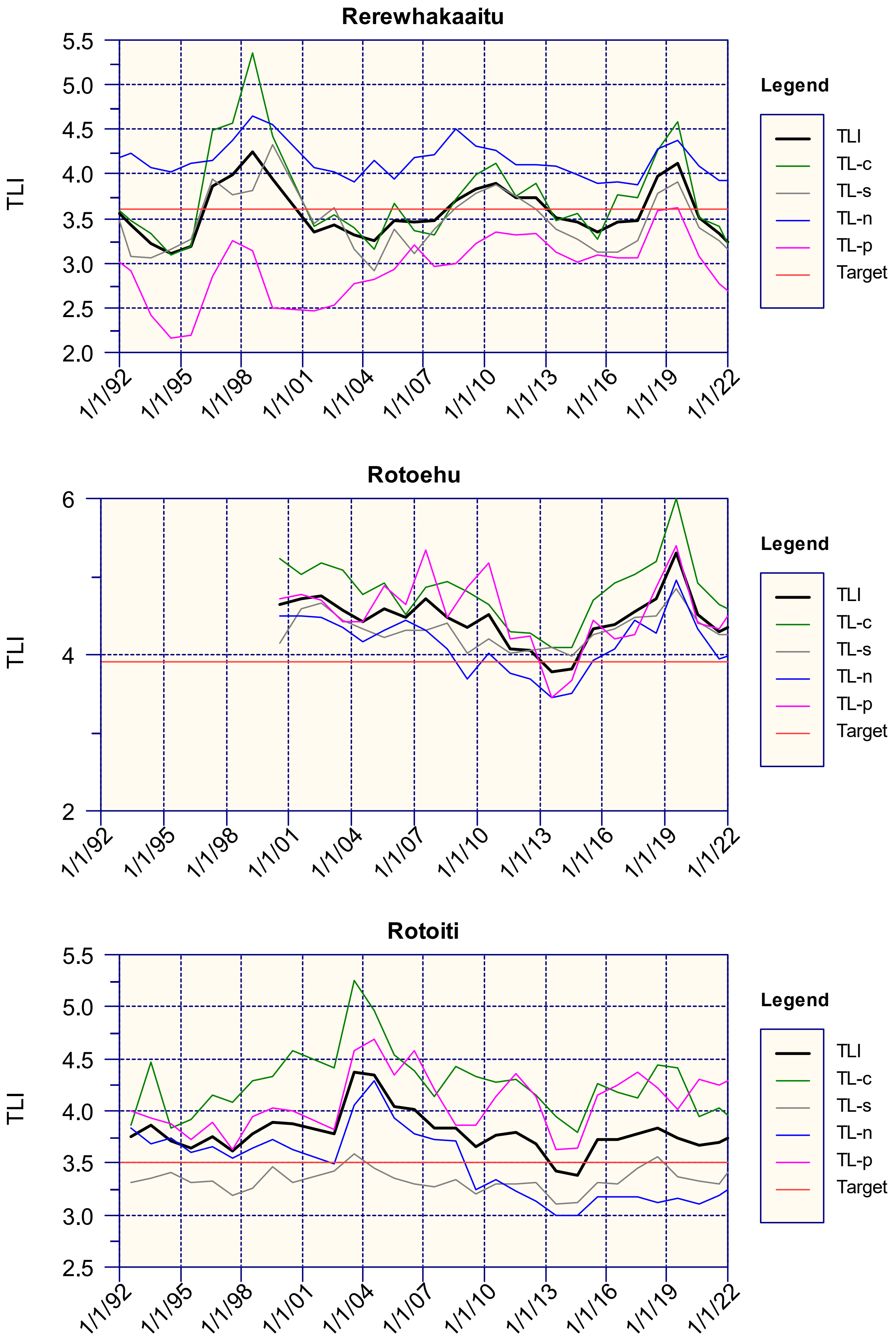


Figure 3.3 b*: Annual mean TLI and targets. Dates are the end of the hydrological year.*

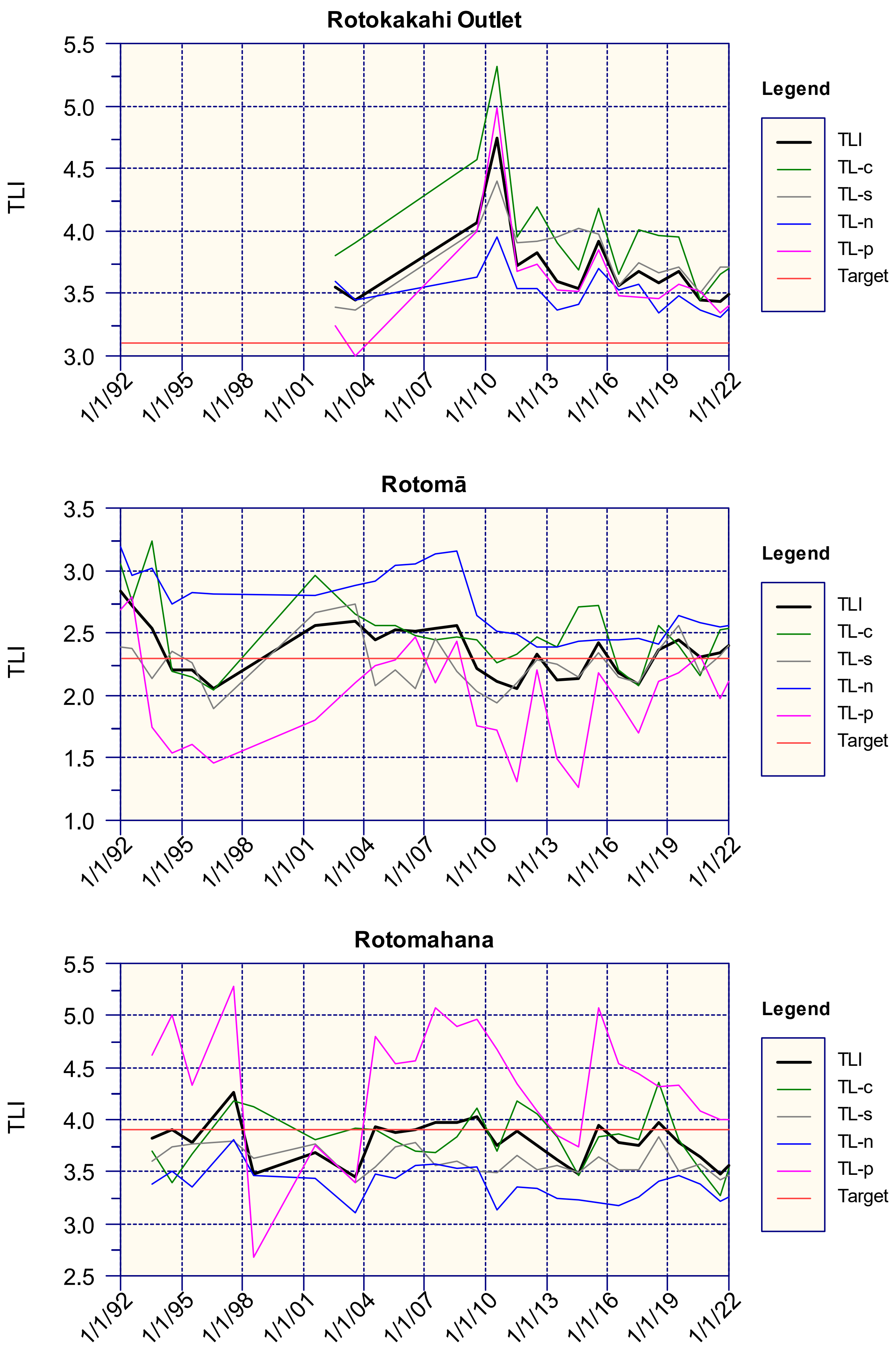


***Figure 3.3 c**: Annual mean TLI and targets. Dates are the end of the hydrological year.*

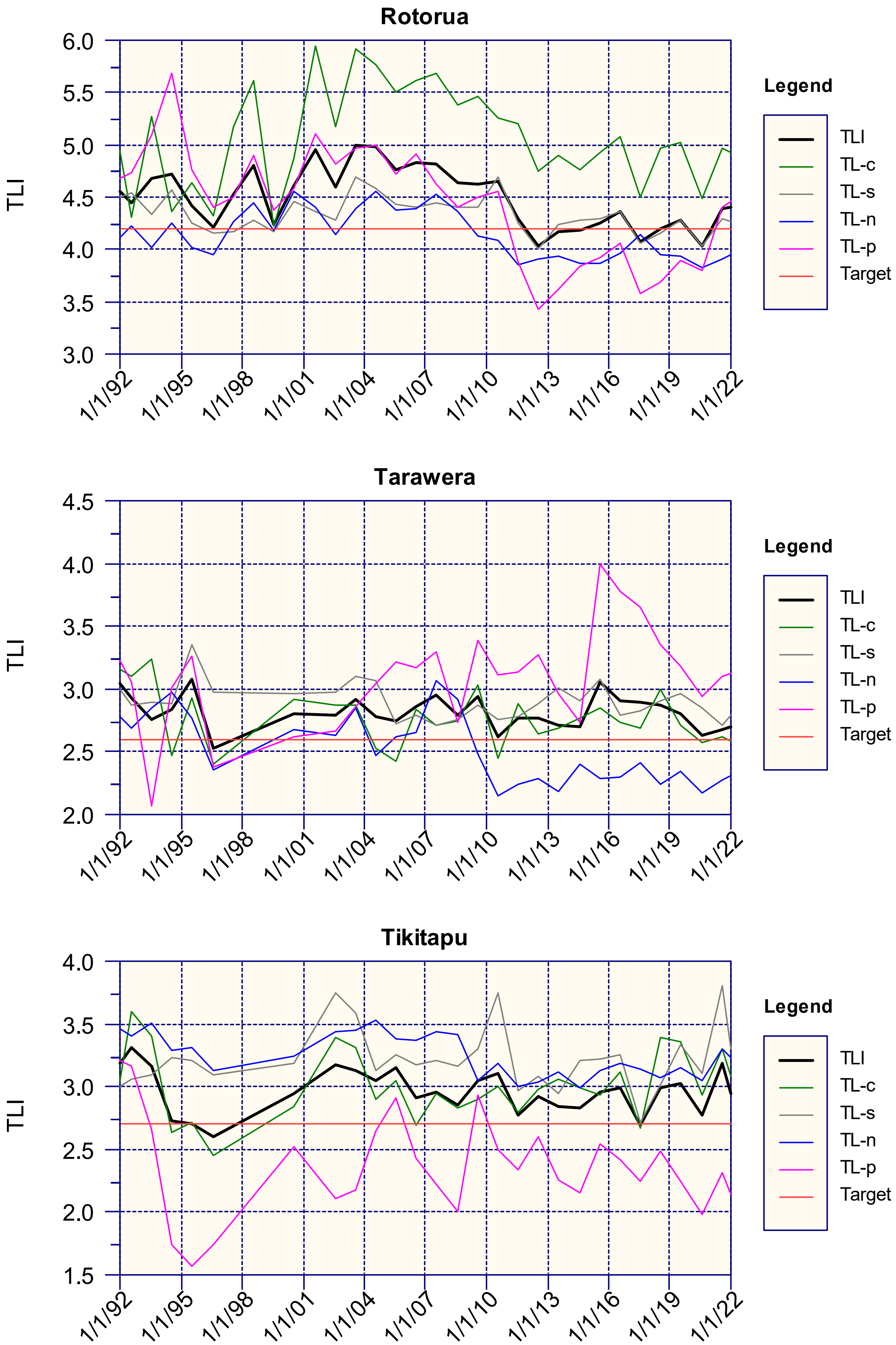


***Figure 3.3 d**: Annual mean TLI and targets. Dates are the end of the hydrological year.*

3.4 Relationship of annual TLI between lakes

The relationship of annual TLI between different lakes is complex, but nevertheless there are a number of occasions when the annual TLI appears to be correlated between lakes. For example, annual TLI was high in many lakes around about 2003, 2012, and 2018, and low in many lakes around 1993/94, 1995/96, and 2015 (**Figure 3.3**). The correlation of annual TLI interannual variability between lakes was tested using a spearman rank correlation test and t-test.

Lakes that have a correlation in the interannual variation of their TLI values might be used as a psedo-control, to test if changes in TLI value due to catchment specific anthropogenic influence or instead influenced by more regional factors like climatic variation or large scale landuse changes. This approach can be use with more confidence when the lakes being used as a control do not have a direct hydrological connection, but even then, should only be viewed as one of multiple lines of evidence from which to draw conclusions.

The interannual variability in annual TLI showed alignment between clusters of lakes (**Table 3.6**), and often these were geographically close. The lakes that most commonly had significant correlations in TLI with other lakes were Rotomā and Lake Ōkataina.

There was moderately strong positive correlation (of 0.6 to 0.7) between the lakes:

- Rotorua, Rotoiti, Rotomā and Ōkataina (**Figure 3.4**).

There were weaker (0.5 to 0.6) but still statistically significant correlations in annual TLI between:

- Rotoiti and Rotoehu (**Figure 3.5**),
- Rotomahana and Tarawera (**Figure 3.6**),
- and between
- Tikitapu, Ōkataina, Rotorua.

Other statistically significant correlations (0.45 to 0.5) were between:

- Ōkataina, Rotomahana and Rotokakahi;
- Rotokakahi and Rerewhakaaitu,
- Ōkāreka, Rotoiti, and Rotoehu;
- Ōkāreka and Rotomahana,
- Rotoehu and Rotomā,
- Okawa Bay and Rotomā.

A negative correlation was found between Okawa Bay and Rotokakahi outlet, and Okawa Bay and Rerewhakaaitu. The annual TLI from Lake Ōkaro was not statistically correlated with other lakes.

__Table 3.6__: Spearman correlation of annual TLI between Te Arawa Lakes. Bolded cells have a statistically significant p-value of <0.05. Shaded cells indicate the strength of the correlation.

Lake	Ōkāreka	Ōkaro	Ōkataina	Rerewhakaaitu	Rotoehu	Rotoiti	Rotoiti Okawa Bay	Rotokakahi Outlet	Rotomā	Rotomahana	Rotorua	Tarawera
Ōkaro	0.17											
Ōkataina	0.37	0.43										
Rerewhakaaitu	0.23	0.15	0.02									
Rotoehu	**0.46**	0.05	0.32	0.23								
Rotoiti	**0.46**	0.41	**0.67**	-0.20	**0.63**							
Rotoiti Okawa Bay	0.09	0.08	0.26	**-0.54**	0.12	0.44						
Rotokakahi Outlet	0.32	-0.07	0.07	**0.49**	-0.06	-0.13	**-0.45**					
Rotomā	0.27	0.23	**0.61**	-0.34	**0.48**	**0.61**	**0.45**	-0.17				
Rotomahana	**0.51**	0.11	**0.47**	0.31	0.27	0.33	-0.14	**0.48**	0.22			
Rotorua	0.18	0.24	**0.60**	-0.35	0.34	**0.70**	0.24	-0.05	**0.62**	0.24		
Tarawera	0.27	0.05	0.31	-0.06	0.29	0.32	0.18	0.34	0.34	**0.60**	0.23	
Tikitapu	0.05	0.10	**0.54**	0.01	0.25	0.27	0.28	-0.19	0.30	0.08	**0.53**	0.12

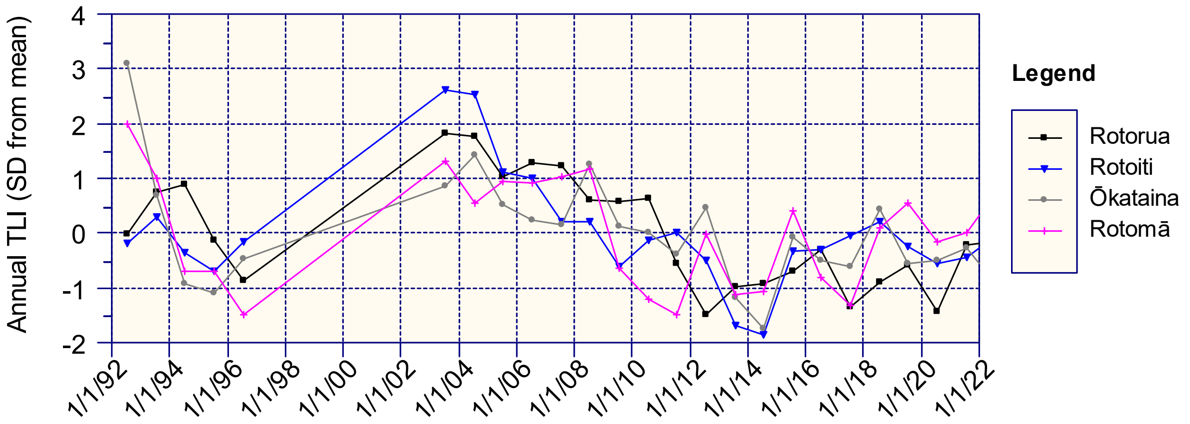


Figure 3.4: Annual TLI expressed as standard deviation from the mean for Lakes Rotorua, Rotoiti, Ōkataina and Rotomā.

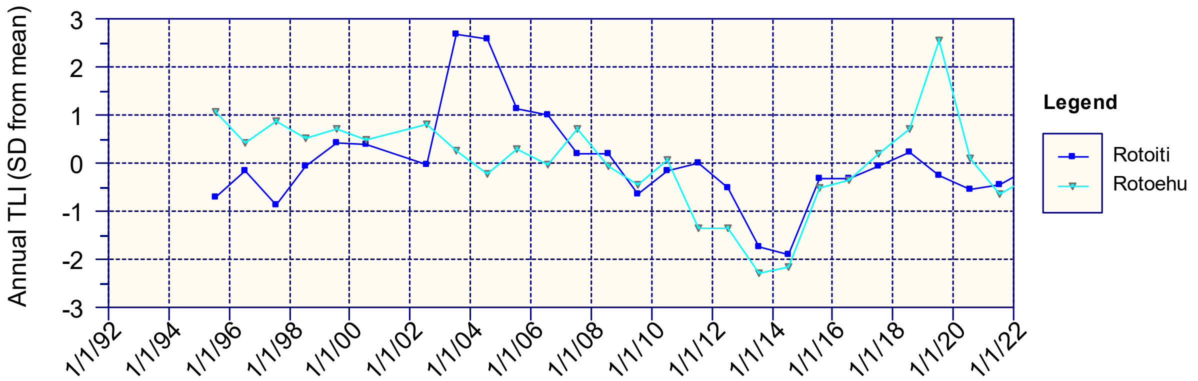


Figure 3.5: Annual TLI expressed as standard deviation from the mean for Lakes Rotoiti and Rotoehu.

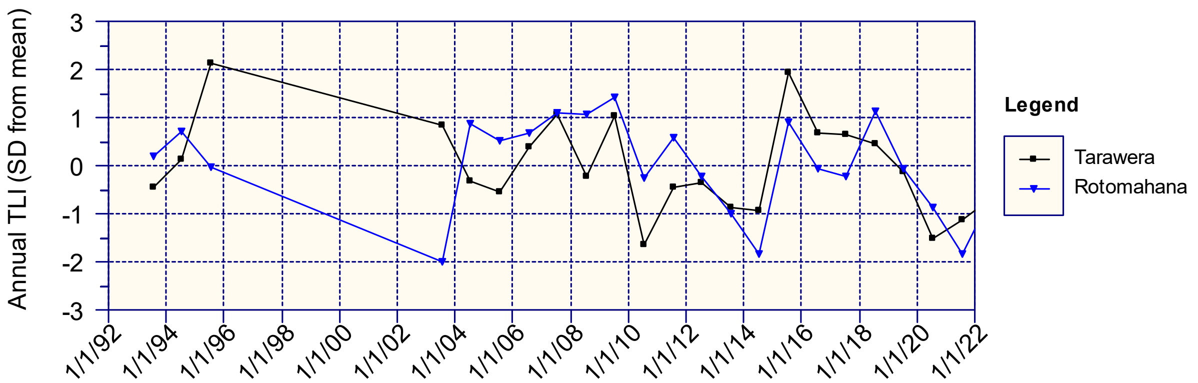


Figure 3.6: Annual TLI expressed as standard deviation from the mean for Lakes Tarawera and Rotomahana.

3.4.1 **Detrended data**

When the data was detrended, the residual interannual data had fewer and weaker statistically significant correlations compared to the original dataset (**Table 3.7**). These were between:

- Rotorua, Rotoiti and Rotomā,
- Rotomahana and Tarawera

Weaker correlations were:

- Ōkāreka and Rotomahana;
- Rotomahana and Rotokakahi
- Ōkataina and Rotomā,
- Ōkataina and Tikitapu,
- Tikitapu and Rotorua,
- Rotomā, Rotoehu

- Rotomā, Rotoiti and Okawa Bay,

A negative correlation was found between Okawa Bay and Rotokakahi outlet, and Okawa Bay and Rerewhakaaitu. The annual TLI from Lake Ōkaro was not statistically correlated with other lakes.

***Table 3.7**: Spearman correlation of annual TLI between Te Arawa Lakes. Bolded cells have a statistically significant p-value of <0.05. Shaded cells indicate the strength of the correlation.*

Lake	Ōkāreka	Ōkaro	Ōkataina	Rerewhakaaitu	Rotoehu	Rotoiti	Rotoiti Okawa Bay	Rotokakahi Outlet	Rotomā	Rotomahana	Rotorua	Tarawera
Ōkaro	0.16											
Ōkataina	0.28	0.00										
Rerewhakaaitu	0.25	0.31	0.07									
Rotoehu	0.24	0.04	0.18	0.14								
Rotoiti	0.36	0.26	0.36	-0.16	0.39							
Rotoiti Okawa Bay	0.08	0.16	0.39	**-0.50**	0.13	**0.47**						
Rotokakahi Outlet	0.33	-0.11	-0.02	**0.53**	-0.01	-0.27	**-0.48**					
Rotomā	0.18	0.16	**0.44**	-0.26	0.41	**0.54**	**0.48**	-0.14				
Rotomahana	**0.48**	0.03	0.29	0.33	0.10	0.30	-0.04	**0.48**	0.11			
Rotorua	0.10	-0.06	0.26	-0.23	0.12	**0.66**	0.21	-0.16	**0.51**	0.21		
Tarawera	0.28	0.00	0.05	-0.05	0.18	0.16	0.20	0.34	0.26	**0.55**	0.12	
Tikitapu	0.02	-0.05	0.44	0.20	0.18	0.13	0.23	-0.14	0.12	0.04	0.43	0.00

4. Review of the TLI

4.1 Expression of TLI for triggering Action Plans

RL M1 (Method 41) of the RNRP sets the process for developing and implementing Action Plans. The development of an Action Plan (and possible regulatory measures) for a lake's catchment is triggered when "*the 3-year moving average TLI for the lake exceeds its [target TLI] by 0.2 for two consecutive years*" (RNRP RL M1 (Method 41) 1b(ii); RL M4 (Method 52)).

The way in which the RNRP (RL M1) expresses the TLI trigger for Action Plans (i.e. the 3-year moving average TLI for the lake exceeds its target TLI by 0.2 for two consecutive years) helps account for natural variability and sampling error. But there may be ways to modify how the TLI is expressed to account for natural variability better.

This section examines the expression of the TLI for comparison with the TLI target for each lake, and the time period used for averaging, the statistic used (e.g. use of a mean compared to a median), and the 0.2 TLI unit tolerance allowed before formal action is triggered.

4.1.1 Assessment period and summary statistic

The influence of the assessment period used for averaging TLI values on the was assessed by calculating the rolling average TLI for durations of 1- to 8-years (**Figure 4.1**). As expected, averaging the TLI over longer periods provides more smoothing and less variation between years. However, longer durations also cause more of a time-lag, which could potentially delay triggering an action plan in response to poor water quality.

The requirement in the RNRP that action plans are not triggered until the TLI target is exceeded for two consecutive years, adds another buffer or delay before triggering action plans. For example, in Lake Rerewhakaaitu the 3-year rolling average TLI exceeded the 3.6 trigger during 1997 to 2001, 2009 to 2013, and 2018 to 2021, but the trigger for action did not occur until 1998, 2010 and 2019.

Table 4.1 compares the effect of the number of years used to average TLI results (1-year, 3-years and 5-years) and the influence of using either the mean or median statistic. The table is shaded to indicate whether the TLI values are above (shades of red), at (white) or below (shades of blue) the target TLI for each lake. The shading indicates a general improvement in TLI values in many lakes over time (e.g. Lakes Ōkaro, Ōkataina, Rotomā, Rotorua), as well as strong interannual variability in some lakes (e.g. Rerewhakaaitu, Rotoehu, Rotoiti, Rotomahana, Rotomā).

A smoother transition between years occurs when using a multi-year mean rather than a median, and when averaging over a longer period. This is apparent in Lake Ōkaro with the lower TLI scores in 2013/14 compared to 2012/13; and in Lakes Rotoehu and Rotoiti with lower TLI scores in 2012/13 compared to 2011/12.

The current approach of using a rolling mean TLI over a three-year period is reasonable from a statistical perspective. Regular monthly sampling provides 36 data points over three years, and as the sample sizes increases above 30 there are diminishing returns with respect to improved confidence in estimates (McBride 2005). Alternatively, a 5-year mean may be a better option to fit with the 5-year reporting periods used for Lake Rotorua.

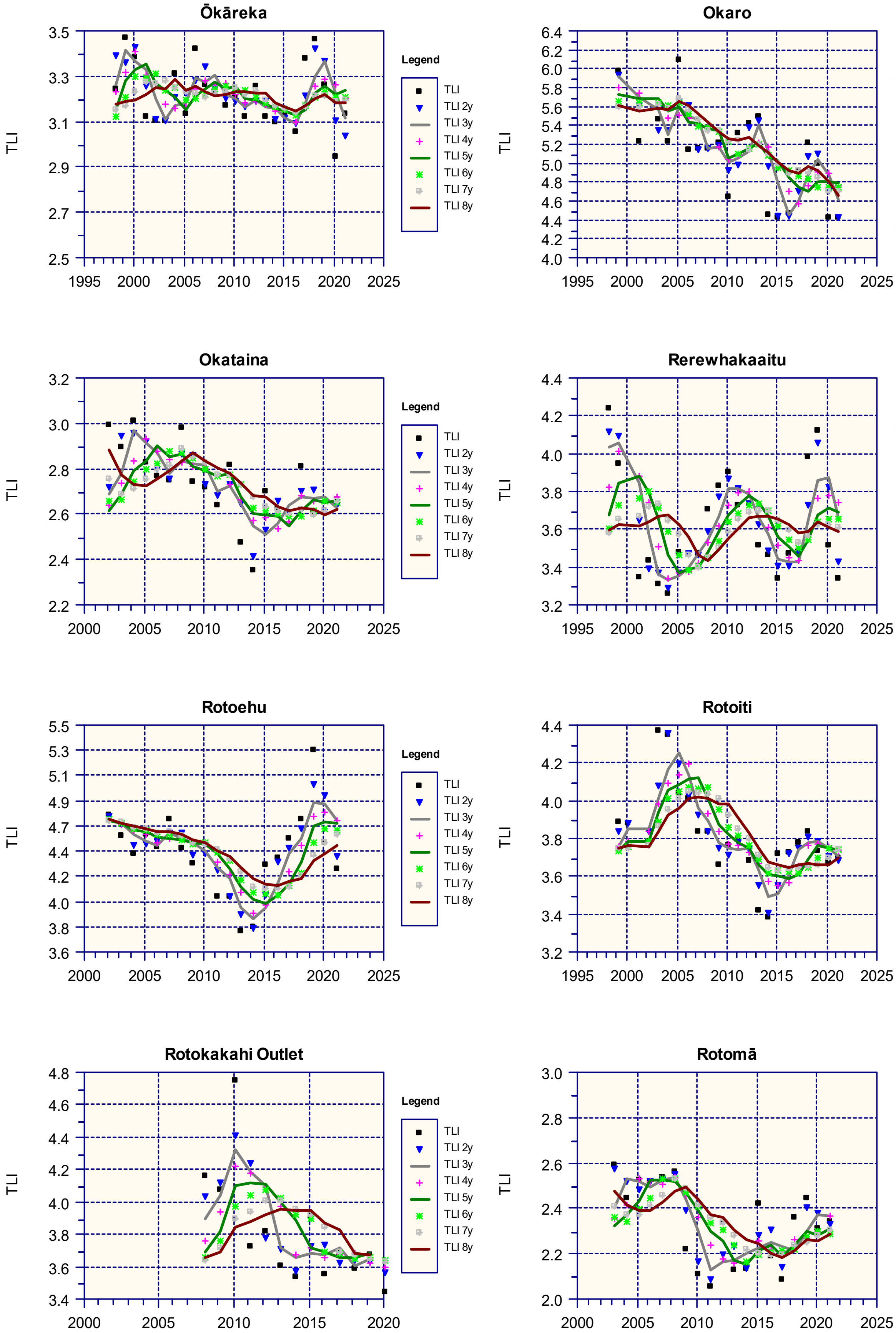


Figure 4.1 a: *Interannual variation in TLI reduces when averaged over increasing periods. Lines indicate TLI expressed as a 3-year, 5-year and 8-year average. Intervals set at 0.2 TLI units.*

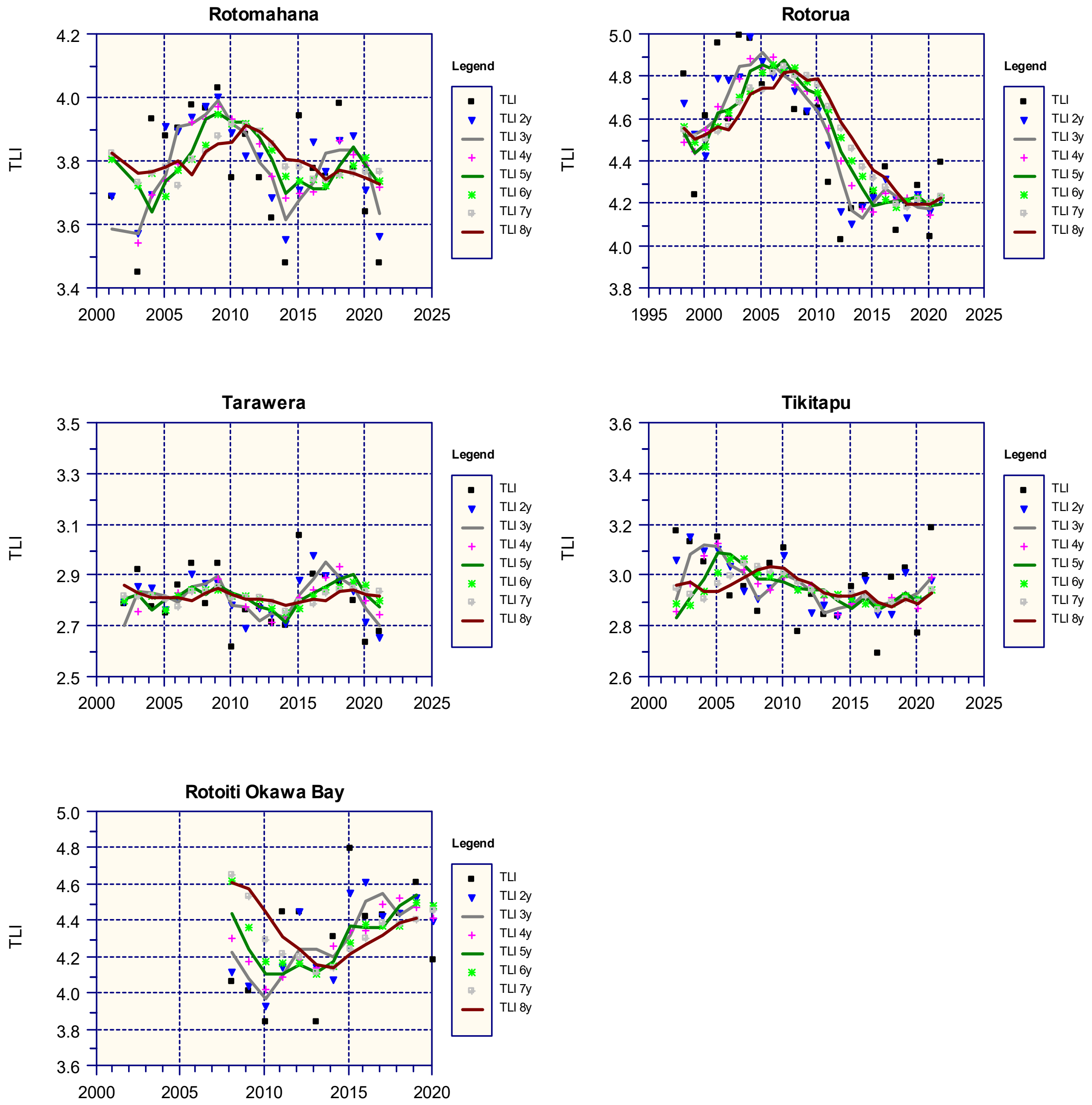


Figure 4.1 b: Interannual variation in TLI reduces when averaged over increasing periods. Lines indicate TLI expressed as a 3-year, 5-year and 8-year average. Intervals set at 0.2 TLI units. Dates are the end of the hydrological year.

***Table 4.1**: Influence of years and statistic used to average TLI. Shading red and blue indicate TLI respectively above and below target.*

	Ōkāreka					Ōkaro					Ōkataina				
		mean		median			mean		median			mean		median	
Year	TLI	TLI 3y	TLI 5y	TLI 3y	TLI 5y	TLI	TLI 3y	TLI 5y	TLI 3y	TLI 5y	TLI	TLI 3y	TLI 5y	TLI 3y	TLI 5y
1990/91	3.4										3.8				
1991/92	3.3					5.6					3.4				
1992/93	3.0	3.2		3.3		5.3					2.9	3.3		3.4	
1993/94	2.8	3.0		3.0		5.3	5.4		5.3		2.5	2.9		2.9	
1994/95	3.2	3.0	3.1	3.0	3.2	5.5	5.3		5.3		2.5	2.6	3.0	2.5	2.9
1995/96	3.0	3.0	3.1	3.0	3.0	5.4	5.4	5.4	5.4	5.4	2.6	2.5	2.8	2.5	2.6
1996/97	3.5	3.2	3.1	3.2	3.0	5.9	5.6	5.5	5.5	5.4					
1997/98	3.2	3.3	3.2	3.2	3.2	5.9	5.7	5.6	5.9	5.5					
1998/99	3.5	3.4	3.3	3.5	3.2	6.0	5.9	5.7	5.9	5.9					
1999/00	3.4	3.4	3.3	3.4	3.4						2.4	2.5	2.6	2.5	2.5
2000/01	3.1	3.3	3.4	3.4	3.4	5.2	5.7	5.7	5.9	5.9					
2001/02	3.1	3.2	3.3	3.1	3.2						3.0	2.7	2.6	2.6	2.5
2002/03	3.1	3.1	3.2	3.1	3.1	5.5	5.6	5.7	5.5	5.9	2.9	2.8	2.7	2.9	2.6
2003/04	3.3	3.2	3.2	3.1	3.1	5.2	5.3	5.6	5.2	5.5	3.0	3.0	2.8	3.0	2.9
2004/05	3.1	3.2	3.2	3.1	3.1	6.1	5.6	5.6	5.5	5.5	2.8	2.9	2.8	2.9	2.9
2005/06	3.4	3.3	3.2	3.3	3.1	5.1	5.5	5.4	5.2	5.2	2.8	2.9	2.9	2.8	2.9
2006/07	3.3	3.3	3.2	3.3	3.3	5.2	5.5	5.4	5.2	5.2	2.7	2.8	2.9	2.8	2.8
2007/08	3.2	3.3	3.3	3.3	3.3	5.2	5.2	5.4	5.2	5.2	3.0	2.8	2.9	2.8	2.8
2008/09	3.2	3.2	3.2	3.2	3.2	5.2	5.2	5.3	5.2	5.2	2.7	2.8	2.8	2.7	2.8
2009/10	3.2	3.2	3.3	3.2	3.2	4.6	5.0	5.1	5.2	5.2	2.7	2.8	2.8	2.7	2.7
2010/11	3.1	3.2	3.2	3.2	3.2	5.3	5.1	5.1	5.2	5.2	2.6	2.7	2.8	2.7	2.7
2011/12	3.3	3.2	3.2	3.2	3.2	5.4	5.1	5.1	5.3	5.2	2.8	2.7	2.8	2.7	2.7
2012/13	3.1	3.2	3.2	3.1	3.2	5.5	5.4	5.2	5.4	5.3	2.5	2.6	2.7	2.6	2.7
2013/14	3.1	3.2	3.2	3.1	3.1	4.5	5.1	5.1	5.4	5.3	2.4	2.5	2.6	2.5	2.6
2014/15	3.1	3.1	3.1	3.1	3.1	4.4	4.8	5.0	4.5	5.3	2.7	2.5	2.6	2.5	2.6
2015/16	3.1	3.1	3.1	3.1	3.1	4.5	4.4	4.9	4.5	4.5	2.6	2.6	2.6	2.6	2.6
2016/17	3.4	3.2	3.2	3.1	3.1	4.9	4.6	4.8	4.5	4.5	2.6	2.6	2.5	2.6	2.6
2017/18	3.5	3.3	3.2	3.4	3.1	5.2	4.9	4.7	4.9	4.5	2.8	2.7	2.6	2.6	2.6
2018/19	3.3	3.4	3.3	3.4	3.3	5.0	5.0	4.8	5.0	4.9	2.6	2.7	2.7	2.6	2.6
2019/20	2.9	3.2	3.2	3.3	3.3	4.4	4.9	4.8	5.0	4.9	2.6	2.7	2.6	2.6	2.6
2020/21	3.1	3.1	3.2	3.1	3.3	4.4	4.6	4.8	4.4	4.9	2.7	2.6	2.7	2.6	2.6

	Rerewhakaaitu					Rotoehu					Rotoiti				
		mean		median			mean		median			mean		median	
Year	TLI	TLI 3y	TLI 5y	TLI 3y	TLI 5y	TLI	TLI 3y	TLI 5y	TLI 3y	TLI 5y	TLI	TLI 3y	TLI 5y	TLI 3y	TLI 5y
1990/91	3.7														
1991/92	3.4										3.8				
1992/93	3.2	3.5		3.4							3.9				
1993/94	3.1	3.3		3.2							3.7	3.8		3.8	
1994/95	3.2	3.2	3.3	3.2	3.2	4.8					3.6	3.7		3.7	
1995/96	3.9	3.4	3.4	3.2	3.2	4.6					3.8	3.7	3.7	3.7	3.8
1996/97	4.0	3.7	3.5	3.9	3.2	4.8	4.7		4.8		3.6	3.7	3.7	3.6	3.7
1997/98	4.2	4.0	3.7	4.0	3.9	4.7	4.7		4.7		3.8	3.7	3.7	3.8	3.7
1998/99	3.9	4.1	3.8	4.0	3.9	4.7	4.7	4.7	4.7	4.7	3.9	3.8	3.7	3.8	3.8
1999/00						4.6	4.7	4.7	4.7	4.7	3.9	3.8	3.8	3.9	3.8
2000/01	3.3	3.8	3.9	3.9	3.9	4.7	4.7	4.7	4.7	4.7					
2001/02	3.4	3.6	3.8	3.4	3.9	4.7	4.7	4.7	4.7	4.7	3.8	3.9	3.8	3.9	3.8
2002/03	3.3	3.4	3.7	3.3	3.4	4.6	4.7	4.7	4.7	4.7	4.4	4.0	3.9	3.9	3.9
2003/04	3.3	3.3	3.5	3.3	3.3	4.4	4.6	4.6	4.6	4.6	4.4	4.2	4.1	4.4	3.9
2004/05	3.5	3.4	3.4	3.3	3.3	4.6	4.5	4.6	4.6	4.6	4.0	4.3	4.1	4.4	4.0
2005/06	3.5	3.4	3.4	3.5	3.4	4.5	4.5	4.6	4.5	4.6	4.0	4.1	4.1	4.0	4.0
2006/07	3.5	3.5	3.4	3.5	3.5	4.7	4.6	4.6	4.6	4.6	3.8	4.0	4.1	4.0	4.0
2007/08	3.7	3.5	3.5	3.5	3.5	4.5	4.6	4.5	4.5	4.5	3.8	3.9	4.0	3.8	4.0
2008/09	3.8	3.7	3.6	3.7	3.5	4.3	4.5	4.5	4.5	4.5	3.7	3.8	3.9	3.8	3.8
2009/10	3.9	3.8	3.7	3.8	3.7	4.5	4.4	4.5	4.5	4.5	3.8	3.8	3.8	3.8	3.8
2010/11	3.7	3.8	3.7	3.8	3.7	4.1	4.3	4.4	4.3	4.5	3.8	3.7	3.8	3.8	3.8
2011/12	3.7	3.8	3.8	3.7	3.7	4.1	4.2	4.3	4.1	4.3	3.7	3.7	3.7	3.8	3.8
2012/13	3.5	3.7	3.7	3.7	3.7	3.8	4.0	4.2	4.1	4.1	3.4	3.6	3.7	3.7	3.7
2013/14	3.5	3.6	3.7	3.5	3.7	3.8	3.9	4.0	3.8	4.1	3.4	3.5	3.6	3.4	3.7
2014/15	3.3	3.4	3.6	3.5	3.5	4.3	4.0	4.0	3.8	4.1	3.7	3.5	3.6	3.4	3.7
2015/16	3.5	3.4	3.5	3.5	3.5	4.4	4.2	4.1	4.3	4.1	3.7	3.6	3.6	3.7	3.7
2016/17	3.5	3.4	3.5	3.5	3.5	4.5	4.4	4.2	4.4	4.3	3.8	3.7	3.6	3.7	3.7
2017/18	4.0	3.6	3.5	3.5	3.5	4.7	4.5	4.4	4.5	4.4	3.8	3.8	3.7	3.8	3.7
2018/19	4.1	3.9	3.7	4.0	3.5	5.3	4.9	4.7	4.7	4.5	3.7	3.8	3.8	3.8	3.7
2019/20	3.5	3.9	3.7	4.0	3.5	4.5	4.8	4.7	4.7	4.5	3.7	3.7	3.8	3.7	3.7
2020/21	3.3	3.7	3.7	3.5	3.5	4.3	4.7	4.7	4.5	4.5	3.7	3.7	3.7	3.7	3.7

Year	Rotokakahi Outlet					Rotomā					Rotomahana				
		mean		median			mean		median			mean		median	
	TLI	TLI 3y	TLI 5y	TLI 3y	TLI 5y	TLI	TLI 3y	TLI 5y	TLI 3y	TLI 5y	TLI	TLI 3y	TLI 5y	TLI 3y	TLI 5y
1990/91						2.9									
1991/92						2.7									
1992/93						2.5	2.7		2.7		3.8				
1993/94						2.2	2.5		2.5		3.9				
1994/95						2.2	2.3	2.5	2.2	2.5	3.8	3.8		3.8	
1995/96						2.1	2.2	2.3	2.2	2.2		3.8		3.8	
1996/97											4.3	4.0	3.9	4.0	3.9
1997/98											3.5	3.9	3.9	3.9	3.8
1998/99												3.9	3.8	3.9	3.8
1999/00	3.8														
2000/01						2.6	2.3	2.3	2.2	2.2	3.7	3.6	3.8	3.6	3.7
2001/02	3.5														
2002/03	3.5	3.6		3.5		2.6	2.4	2.3	2.6	2.2	3.4	3.6	3.7	3.6	3.6
2003/04	3.4	3.5		3.5		2.4	2.5	2.4	2.6	2.4	3.9	3.7	3.6	3.7	3.6
2004/05	3.3	3.4	3.5	3.4	3.5	2.5	2.5	2.4	2.5	2.5	3.9	3.8	3.7	3.9	3.8
2005/06	3.6	3.5	3.5	3.4	3.5	2.5	2.5	2.5	2.5	2.5	3.9	3.9	3.8	3.9	3.9
2006/07	3.9	3.6	3.6	3.6	3.5	2.5	2.5	2.5	2.5	2.5	4.0	3.9	3.8	3.9	3.9
2007/08	4.2	3.9	3.7	3.9	3.6	2.6	2.5	2.5	2.5	2.5	4.0	3.9	3.9	4.0	3.9
2008/09	4.1	4.0	3.8	4.1	3.9	2.2	2.4	2.5	2.5	2.5	4.0	4.0	4.0	4.0	4.0
2009/10	4.7	4.3	4.1	4.2	4.1	2.1	2.3	2.4	2.2	2.5	3.7	3.9	3.9	4.0	4.0
2010/11	3.7	4.2	4.1	4.1	4.1	2.1	2.1	2.3	2.1	2.2	3.9	3.9	3.9	3.9	4.0
2011/12	3.8	4.1	4.1	3.8	4.1	2.3	2.2	2.3	2.1	2.2	3.7	3.8	3.9	3.7	3.9
2012/13	3.6	3.7	4.0	3.7	3.8	2.1	2.2	2.2	2.1	2.1	3.6	3.8	3.8	3.7	3.7
2013/14	3.5	3.7	3.9	3.6	3.7	2.1	2.2	2.2	2.1	2.1	3.5	3.6	3.7	3.6	3.7
2014/15	3.9	3.7	3.7	3.6	3.7	2.4	2.2	2.2	2.1	2.1	3.9	3.7	3.7	3.6	3.7
2015/16	3.6	3.7	3.7	3.6	3.6	2.2	2.2	2.2	2.2	2.2	3.8	3.7	3.7	3.8	3.7
2016/17	3.7	3.7	3.7	3.7	3.6	2.1	2.2	2.2	2.2	2.1	3.8	3.8	3.7	3.8	3.8
2017/18	3.6	3.6	3.7	3.6	3.6	2.4	2.2	2.2	2.2	2.2	4.0	3.8	3.8	3.8	3.8
2018/19	3.7	3.6	3.7	3.7	3.7	2.4	2.3	2.3	2.4	2.4	3.8	3.8	3.8	3.8	3.8
2019/20	3.4	3.6	3.6	3.6	3.6	2.3	2.4	2.3	2.4	2.3	3.6	3.8	3.8	3.8	3.8
2020/21	3.4	3.5	3.6	3.4	3.6	2.3	2.4	2.3	2.3	2.3	3.5	3.6	3.7	3.6	3.8

Year	Rotorua					Tarawera					Tikitapu				
		mean		median			mean		median			mean		median	
	TLI	TLI 3y	TLI 5y	TLI 3y	TLI 5y	TLI	TLI 3y	TLI 5y	TLI 3y	TLI 5y	TLI	TLI 3y	TLI 5y	TLI 3y	TLI 5y
1990/91	4.7					3.2					3.1				
1991/92	4.5					2.9					3.3				
1992/93	4.7	4.6		4.7		2.8	2.9		2.9		3.2	3.2		3.2	
1993/94	4.7	4.6		4.7		2.8	2.8		2.8		2.7	3.1		3.2	
1994/95	4.4	4.6	4.6	4.7	4.7	3.1	2.9	3.0	2.8	2.9	2.7	2.9	3.0	2.7	3.1
1995/96	4.2	4.4	4.5	4.4	4.5	2.5	2.8	2.8	2.8	2.8	2.6	2.7	2.9	2.7	2.7
1996/97	4.5	4.4	4.5	4.4	4.5										
1997/98	4.8	4.5	4.5	4.5	4.5										
1998/99	4.2	4.5	4.4	4.5	4.4										
1999/00	4.6	4.6	4.5	4.6	4.5	2.8	2.8	2.8	2.8	2.8	2.9	2.8	2.8	2.7	2.7
2000/01	5.0	4.6	4.6	4.6	4.6										
2001/02	4.6	4.7	4.6	4.6	4.6	2.8	2.7	2.8	2.8	2.8	3.2	2.9	2.8	2.9	2.7
2002/03	5.0	4.8	4.7	5.0	4.6	2.9	2.8	2.8	2.8	2.8	3.1	3.1	2.9	3.1	2.9
2003/04	5.0	4.9	4.8	5.0	5.0	2.8	2.8	2.8	2.8	2.8	3.1	3.1	3.0	3.1	3.1
2004/05	4.8	4.9	4.9	5.0	5.0	2.7	2.8	2.8	2.8	2.8	3.1	3.1	3.1	3.1	3.1
2005/06	4.8	4.9	4.8	4.8	4.8	2.9	2.8	2.8	2.8	2.8	2.9	3.0	3.1	3.1	3.1
2006/07	4.8	4.8	4.9	4.8	4.8	2.9	2.9	2.9	2.9	2.9	3.0	3.0	3.0	3.0	3.1
2007/08	4.6	4.8	4.8	4.8	4.8	2.8	2.9	2.8	2.9	2.8	2.9	2.9	3.0	2.9	3.0
2008/09	4.6	4.7	4.7	4.6	4.8	2.9	2.9	2.9	2.9	2.9	3.0	3.0	3.0	3.0	3.0
2009/10	4.6	4.6	4.7	4.6	4.6	2.6	2.8	2.8	2.8	2.9	3.1	3.0	3.0	3.0	3.0
2010/11	4.3	4.5	4.6	4.6	4.6	2.8	2.8	2.8	2.8	2.8	2.8	3.0	2.9	3.0	3.0
2011/12	4.0	4.3	4.4	4.3	4.6	2.8	2.7	2.8	2.8	2.8	2.9	2.9	2.9	2.9	2.9
2012/13	4.2	4.2	4.4	4.2	4.3	2.7	2.7	2.8	2.8	2.8	2.8	2.8	2.9	2.8	2.9
2013/14	4.2	4.1	4.3	4.2	4.2	2.7	2.7	2.7	2.7	2.7	2.8	2.9	2.9	2.8	2.8
2014/15	4.3	4.2	4.2	4.2	4.2	3.1	2.8	2.8	2.7	2.8	3.0	2.9	2.9	2.8	2.8
2015/16	4.4	4.3	4.2	4.3	4.2	2.9	2.9	2.8	2.9	2.8	3.0	2.9	2.9	3.0	2.9
2016/17	4.1	4.2	4.2	4.3	4.2	2.9	2.9	2.9	2.9	2.9	2.7	2.9	2.9	3.0	2.8
2017/18	4.2	4.2	4.2	4.2	4.2	2.9	2.9	2.9	2.9	2.9	3.0	2.9	2.9	3.0	3.0
2018/19	4.3	4.2	4.2	4.2	4.3	2.8	2.9	2.9	2.9	2.9	3.0	2.9	2.9	3.0	3.0
2019/20	4.0	4.2	4.2	4.2	4.2	2.6	2.8	2.8	2.8	2.9	2.8	2.9	2.9	3.0	3.0
2020/21	4.4	4.2	4.2	4.3	4.2	2.7	2.7	2.8	2.7	2.8	3.2	3.0	2.9	3.0	3.0

4.1.2 **Use of a 0.2 TLI unit tolerance before requiring action**

Three-year rolling average TLI values need to exceed the lake TLI target by 0.2 TLI units (for two consecutive years) before triggering Action Plans. The 0.2 TLI unit tolerance is less than the interannual variability observed in most of the lakes after linear trends have been removed, similar to the interannual variability observed in oligotrophic lakes of Rotomā and Ōkataina (and Ōkāreka), but more than occurs in Lakes Tarawera and Tikitapu (**Table 4.2**). It could be argued on the basis of historical statistics that the current 0.2 tolerance is too lenient for Tarawera and Tikitapu, and too strict for some other lakes that have high interannual variability in three-year average TLI (e.g. Okaro, Rerewhakaaitu, Rotoehu, Rotoiti, Rotokakahi, and Rotorua). However, for eutrophic lakes (or worse), the interannual variability may not be a good way to determine an acceptable tolerance because poor water quality conditions are associated with larger variability. Furthermore, in some lakes the large TLI variability expressed in the statistics is strongly influenced by periods of unacceptably poor water quality (e.g. Rotoehu algae blooms during 2019, Rotorua and Rotoiti during 2003-2004).

Another important consideration is the extent to which any tolerance applied to the targets would allow water quality to decline. A 0.2 TLI-unit increase in a lake with a TLI of 4, equates to 0.5m decline in Secchi depth (3.5m to 3.0m) (25% decline); while a 0.2 TLI-unit increase in a lake with a TLI of 3 equates to a 1.0m reduction in Secchi depth (7.7m to 6.7m). Increasing a tolerance from 0.2-units to, for example 0.4-units, would approximately double the decline in Secchi depth clarity allowed by the tolerance (i.e., allowing a 1.0m decline for a lake of TLI 3 and a 2m decline for a lake of TLI 4). If a TLI-tolerance is set too high, then there is a risk that it could effectively allow periodically poor water quality as an acceptable feature of the lake target. The acceptability of this will depend on both lake specific ecological responses and community expectations.

One way to account for interannual variability of individual lakes would be statistically compare the TLI between two time periods (e.g. between the latest five annual values versus previous five-year annual values). Using an equivalence test (McBride et al. 2014) would allow this to be done while incorporating a previously determined “acceptable” tolerance.

4.1.3 **Summary**

The RNRP (RL M1) requires the development of Action Plans for lakes if a lake’s three-year moving average TLI exceeds the lake’s target TLI by 0.2 TLI units for two consecutive years. The approach of using a three-year moving average TLI that needs to exceed a trigger for two consecutive years, appears to provide a reasonable compromise between smoothing short-term variations in the TLI while still enabling timely action. The use of a uniform 0.2 TLI-unit tolerance is within the 95th percentile range of interannual variability in oligotrophic lakes, and thus provides a reasonable estimate of interannual variability in the absence of eutrophication. A slightly larger tolerance (e.g. 0.25) could be considered for some eutrophic lakes which have larger interannual variability, but this would need to be capped to be less than the historical interannual variability to avoid entrenching periodically poor water quality as part of the lake target.

Rather than increase the tolerance, a more robust approach to account for interannual variability is to uses statistical tests over consecutive time periods (e.g., 5-year intervals), and to interpret TLI scores in the context of variability occurring in other lakes and due to climatic factors.

***Table 4.2**: Statistics for 3-year average TLI after removing linear trend over the period 1992 – 2022. Showing mean, standard deviation, 95 percentile distance from mean. Shaded cells indicate oligotrophic lakes (blue) and eutrophic/supertrophic lakes (red).*

		1992 - 2022 detrended			
Lake	**TLI Target**	**TLI mean**	**TLI 95 %ile**	**TLI SD**	**95%ile - mean**
Ōkāreka	3	3.2	3.4	0.11	0.19
Ōkaro	5	5.1	5.5	0.23	0.44
Ōkataina	2.6	2.7	2.9	0.16	0.22
Rerewhakaaitu	3.6	3.6	4.1	0.23	0.48
Rotoehu	3.9	4.5	5.0	0.25	0.50
Rotoiti	3.5	3.8	4.2	0.17	0.37
Rotoiti Okawa Bay		4.5	5.1	0.30	0.62
Rotokakahi Outlet	3.1	3.7	4.2	0.24	0.51
Rotomā	2.3	2.3	2.5	0.14	0.20
Rotomahana	3.9	3.8	3.9	0.12	0.17
Rotorua	4.2	4.6	4.9	0.20	0.34
Tarawera	2.6	2.8	2.9	0.07	0.13
Tikitapu	2.7	2.9	3.0	0.11	0.14

4.2 Influence of TLI calculation method

The precise method used to calculate the TLI influences the results. Burns (2000) specifies calculating TLI by logging annual mean values (“log of means”), but an alternative method often used to allow trend analysis is to calculate TLI for each separate sample occasion and average for each year/period (“mean of logs”). The main difference in the two methods is the point at which the log function is applied to the data. If the dataset is skewed to the right (as is common with lake water quality data), then the alternative method (“mean of logs”) will result in lower values as the log function reduces the more extreme values prior to averaging.

This issue has been discussed in previous reports. Hudson et al. (2011) found that the “log of means” method over-estimated TLI by about 7%, but that his varied widely between lakes and years. Davies-Colley et al (2012) recognised this issue and recommended that for national reporting, to use the “mean of logs” method, i.e. calculate the TLI index separately for each sampling occasion separately <u>before</u> averaging the TLI values into an annual mean TLI. Schallenberg and van der Zon (2021) took the opposite view. They recognised that using the annual average of monthly TLI data had statistical advantages but recommended using the “log of means” method because it is consistent with the protocols developed by Burns et al (2000), and so ensures TLI values are “*properly calibrated and are comparable*”. The relevance of retaining the “log of means” method to ensure proper calibration is questionable because in developing the TLI Burns et al (2000) used lake data only for developing equations for TN (TL-n), TP (TL-p) and Sechi depth (TL-s) relative to chlorophyll-*a* (TL-c)

Comparing the two methods for the Te Arawa /Rotorua lakes shows that the “mean of logs” method results in <u>lower</u> annual TLI scores for all lakes (**Table 4.3**). On average, the annual TLI using the “mean of logs” method was 0.7% to 3.7% lower than using the “log of means” method, which is considerably less than the standard deviation in annual TLI scores between years. The lake with the highest difference between methods was Lake Ōkaro (0.21 TLI units) and the lowest was Lake Rotomā (0.3 TLI units), reflecting their relative difference in trophic status. In terms of percent change, the method made the largest difference in Lake Okaro (3.7%), and Lake Rotomā (3.1%), and made the least difference in Lake Rotorua (0.7%).

A comparison of the calculation method for each TLI component (**Figure 4.2**) shows that the calculation method had most influence on the chlorophyll-*a* component (TL-c) of the TLI, probably due to higher variability in chlorophyll-*a*. Unlike other variables, for Secchi depth (TL-s) the "mean of logs" method results in higher annual TLI scores because the Secchi depth distribution tends to be negatively skewed. For this reason, the difference between the two calculation methods is likely to be more extreme if Secchi depth is not included in the TLI calculation (i.e. TLI3).

The analysis confirms the conclusions of previous reports about the importance of following a consistent method for calculating TLI scores and for reporting against the target values. It also supports the practice of applying a small tolerance as a buffer before triggering development of action plans.

***Table 4.3**: Comparison of annual TLI calculated by the alternative methods of "log of means" and "mean of logs". Average and median statistics shown for the period July 2002 to July 2001.*

	Average TLI				Median TLI			
Lake	"log of means"	"mean of logs"	Difference	% Difference	"log of means"	"mean of logs"	Difference	% Difference
Ōkāreka	3.20	3.16	-0.04	-1.2%	3.17	3.13	-0.04	-1.3%
Ōkaro	5.03	4.85	-0.18	-3.7%	5.15	4.95	-0.21	-4.0%
Ōkataina	2.72	2.66	-0.06	-2.2%	2.72	2.66	-0.06	-2.1%
Rerewhakaaitu	3.59	3.55	-0.04	-1.1%	3.48	3.49	0.01	0.2%
Rotoehu	4.42	4.35	-0.06	-1.4%	4.47	4.39	-0.09	-1.9%
Rotoiti	3.81	3.76	-0.05	-1.2%	3.76	3.72	-0.04	-1.1%
Rotokakahi Outlet	3.72	3.66	-0.06	-1.6%	3.62	3.61	-0.01	-0.2%
Rotomā	2.33	2.26	-0.07	-3.1%	2.34	2.28	-0.07	-2.9%
Rotomahana	3.79	3.74	-0.04	-1.2%	3.78	3.77	-0.01	-0.2%
Rotorua	4.45	4.42	-0.03	-0.7%	4.37	4.30	-0.07	-1.6%
Tarawera	2.81	2.75	-0.06	-2.0%	2.79	2.76	-0.03	-1.2%
Tikitapu	2.96	2.89	-0.07	-2.5%	2.96	2.88	-0.07	-2.5%
Rotoiti Okawa Bay	4.43	4.33	-0.10	-2.2%	4.44	4.35	-0.09	-2.0%

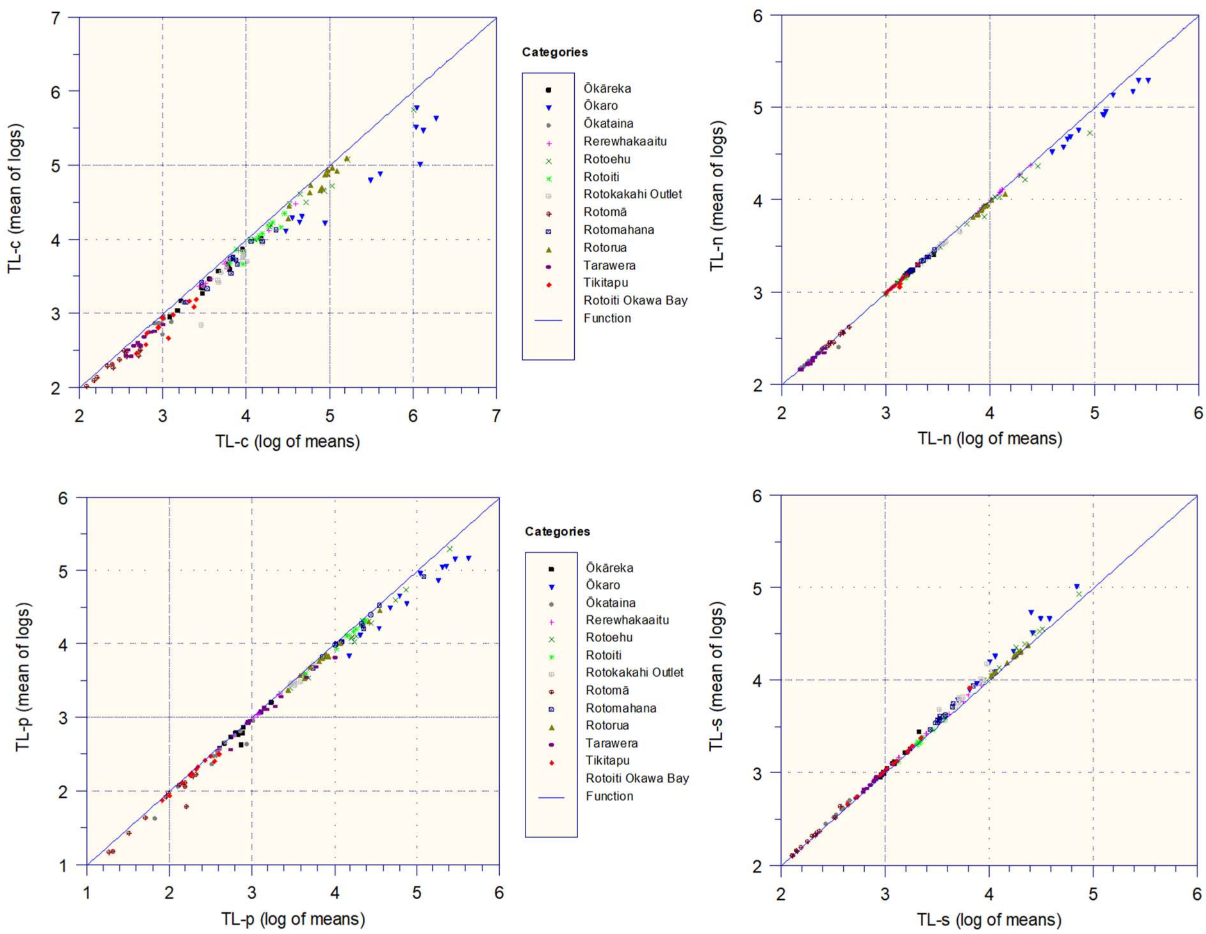


Figure 4.2: Influence of the calculation method ("log of mean" compared to "mean of logs") for components of the TLI (data from Rotorua lakes for the period 2010 to 2022).

4.3 Climatic drivers of interannual variability of TLI

4.3.1 Correlation with climatic factors

Potential climatic drivers of inter-annual variability of TLI within each lake was assessed by comparing TLI (i.e. a 12 month running mean) with climatic variables expressed also expressed as a 12-month running mean. In the case of rainfall, a two-year and three-year mean were also assessed to account for potential delay in responses. The climatic variables assessed were: annual rainfall, Rotomā water level (as a proxy for groundwater levels due to it having few surface inflows and no surface outlet), mean annual wind velocity, mean annual sunshine hours, and mean annual southern oscillation index (**SOI**).

There were strong correlations between the different climatic variables. The SOI measures the difference in atmospheric pressure in the south pacific, which indicates the strength of El Niño and La Niña weather conditions. El Niño conditions (SOI <-0.5 to <-1) in New Zealand are associated with more westerly winds, dryer conditions in the east and more rain in the west; while La Niña conditions (SOI >0.5 to >1) are associated with more common easterly winds, bringing moist, rainy conditions to northeastern areas of the North Island. This pattern is clearly seen in **Figure 4.3** where periods of El

Niño correspond to more rain, higher water levels in Lake Rotomā, and (in some years) fewer sunshine hours.

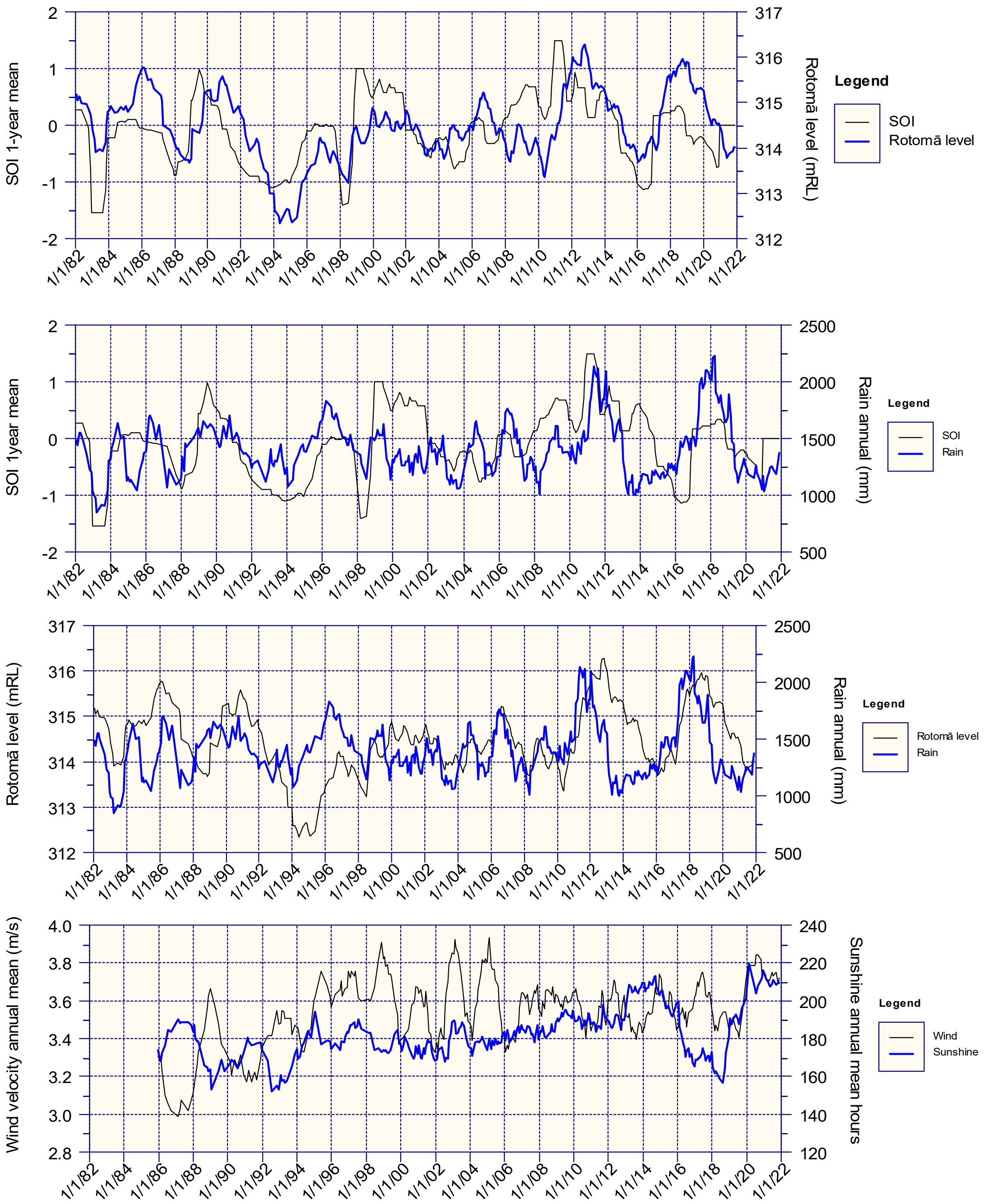


Figure 4.3: Change in climatic variables over time as measured in Rotorua.

The TLI component variables (TL-n, TL-n, TP-c, TP-s) tended to be more strongly correlated to each other in the more eutrophic and mesotrophic lakes, and less strongly correlated in the oligotrophic lakes (Ōkataina, Rotoiti, Rotomā, Tarawera, Tikitapu) and Rotomahana – but the correlations were mostly still statistically significant (**Table 4.5**).

Correlations between TLI and climate variables were identified using a non-parametric spearman correlation for the period 2009-2022 (**Table 4.4, Table 4.5**). Similar, but weaker, correlations were apparent for longer time-period 2001 to 2022. Note interventions to improve lake water quality will affect correlations with climate, and many of these interventions were initiated around the 2009 period.

No single climate variable had good correlations with TLI in all of the lakes. The climate variable that best correlated with TLI in most lakes was annual rainfall as a 2-year running mean. This might be suitable for explaining interannual variation in TLI for Lakes Ōkāreka, Ōkaro, Ōkataina, Rerewhakaaitu, Rotoehu (weak), Rotoiti (1-yr rain better), Rotokakahi (weak, SOI better), and Rotomahana. TLI in Rotomā, Tarawera and Tikitapu had a negative correlation with SOI (related to TP) and Rotorua TLI had a negative correlation with the water level in Rotomā (**Table 4.4**).

The relationship between TLI and rainfall over time is illustrated in **Figure 4.4**. This indicates the positive associated between annual rainfall patterns and annual TLI in many lakes, but with different strengths and time lags.

For some lakes it may be reasonable to develop functions to explain TLI variation due to rainfall (e.g. 2-year moving average) or some other climatic variable. This was explored by running a linear regression through a scatter plot of TLI (1 year-mean) and rainfall (2-year mean) (**Figure 4.5**). Annual rainfall (expressed as a 2-year mean) could explain 43% to 70% of the TLI interannual variability for lakes Ōkāreka, Ōkaro, Ōkataina, Rerewhakaaitu, Rotoiti and Rotomahana. Those regressions that explain a high proportion of variability have potential to be used to adjust the TLI target by using the difference in the rainfall at the time of assessment and the rainfall during ca. 1993/94 (the years used for setting TLI targets in many of the lakes). Annual rainfall during 1993/94 was relatively low (1250mm) compared to the long-term record (1400mm in period 1975-2022) (**Figure 4.3**).

Table 4.4: Summary of spearman correlation (rho) between the 12-month mean TLI and annualised climate variables (2009-2022). Colours indicate the strength and direction of correlation.

Lake	SOI	Rain	rain 2-yr	Sunshine	Rotoma level	Strongest correlation
Ōkāreka	0.28	0.65	0.74	-0.74	0.41	rain 2yr, sunshine (-ve)
Ōkaro	0.63	0.43	0.76	-0.35	0.59	rain 2yr
Ōkataina	0.26	0.50	0.48	-0.35	-0.01	rain 1yr, rain 2 yr
Rerewhakaaitu	0.50	0.49	0.69	-0.45	0.38	rain 2 yr
Rotoehu	-0.32	0.29	0.32	-0.37	-0.07	rain 2 yr, SOI, sunshine (-ve)
Rotoiti	0.11	0.70	0.47	-0.66	-0.12	Rain 1 yr
Rotoiti Okawa Bay	-0.23	0.36	0.31	-0.22	0.22	rain 1 yr, rain 2 yr
Rotokakahi Outlet	0.56	0.20	0.23	-0.24	-0.04	SOI
Rotomā	-0.60	-0.21	-0.07	-0.05	0.03	SOI (-ve)
Rotomahana	0.22	0.62	0.58	-0.61	0.1	rain 1 yr, rain 2 yr
Rotorua	0.17	0.04	-0.18	-0.13	-0.67	Rotoma level (-ve)
Tarawera	-0.32	0.24	0.18	-0.45	0.07	sunshine (-ve)
Tikitapu	-0.31	-0.11	-0.12	0.09	-0.31	SOI, Rotoma level (-ve)

***Table 4.5 a**: Spearman correlation between variables (period 2009-2022)*

Group: Okareka

	TLI yr	TL-n yr	TL-p yr	TL-c yr	TL-s yr	SOI 1yr rolling	Rain annual (mm)	Rain 2 yr mean	Rain 3 yr mean	sunshine annual mean hr
TL-n yr	0.64									
TL-p yr	0.57	0.35								
TL-c yr	0.75	0.37	0.13							
TL-s yr	0.53	0.34	0.54	0.09						
SOI 1yr rolling	0.28	0.22	-0.33	0.62	-0.42					
Rain annual (mm)	0.65	0.61	0.17	0.70	0.31	0.44				
Rain 2 yr mean	0.74	0.43	0.24	0.84	0.36	0.41	0.80			
Rain 3 yr mean	0.58	0.24	0.22	0.74	0.11	0.40	0.51	0.83		
sunshine annual mean hr	-0.74	-0.60	-0.40	-0.61	-0.48	-0.21	-0.81	-0.72	-0.43	
Wind vel annual mean (m/s)	-0.31	-0.15	-0.13	-0.20	-0.05	-0.19	-0.07	-0.21	-0.35	0.27

Significance (2-tailed t-test) of correlations (N = 137)

	TLI yr	TL-n yr	TL-p yr	TL-c yr	TL-s yr	SOI 1yr rolling	Rain annual (mm)	Rain 2 yr mean	Rain 3 yr mean	sunshine annual mean hr
TL-n yr	0.000									
TL-p yr	0.000	0.000								
TL-c yr	0.000	0.000	0.123							
TL-s yr	0.000	0.000	0.000	0.312						
SOI 1yr rolling	0.001	0.011	0.000	0.000	0.000					
Rain annual (mm)	0.000	0.000	0.043	0.000	0.000	0.000				
Rain 2 yr mean	0.000	0.000	0.005	0.000	0.000	0.000	0.000			
Rain 3 yr mean	0.000	0.004	0.011	0.000	0.206	0.000	0.000	0.000		
sunshine annual mean hr	0.000	0.000	0.000	0.000	0.000	0.016	0.000	0.000	0.000	
Wind vel annual mean (m/s)	0.00	0.08	0.14	0.02	0.57	0.03	0.41	0.01	0.00	0.00

Group: Okaro

	TLI yr	TL-n yr	TL-p yr	TL-c yr	TL-s yr	SOI 1yr rolling	Rain annual (mm)	Rain 2 yr mean	Rain 3 yr mean	sunshine annual mean hr
TL-n yr	0.92									
TL-p yr	0.89	0.79								
TL-c yr	0.96	0.85	0.80							
TL-s yr	0.92	0.92	0.72	0.90						
SOI 1yr rolling	0.63	0.68	0.51	0.60	0.63					
Rain annual (mm)	0.43	0.38	0.37	0.39	0.41	0.42				
Rain 2 yr mean	0.76	0.64	0.76	0.72	0.67	0.43	0.79			
Rain 3 yr mean	0.77	0.64	0.81	0.73	0.67	0.43	0.47	0.82		
sunshine annual mean hr	-0.35	-0.30	-0.20	-0.35	-0.36	-0.18	-0.80	-0.70	-0.39	
Wind vel annual mean (m/s)	-0.36	-0.42	-0.20	-0.32	-0.44	-0.18	-0.01	-0.16	-0.33	0.24

Significance (2-tailed t-test) of correlations (N = 141)

Variable	TLI yr	TL-n yr	TL-p yr	TL-c yr	TL-s yr	SOI 1yr rolling	Rain annual (mm)	Rain 2 yr mean	Rain 3 yr mean	sunshine annual mean hr
TL-n yr	0.000									
TL-p yr	0.000	0.000								
TL-c yr	0.000	0.000	0.000							
TL-s yr	0.000	0.000	0.000	0.000						
SOI 1yr rolling	0.000	0.000	0.000	0.000	0.000					
Rain annual (mm)	0.000	0.000	0.000	0.000	0.000	0.000				
Rain 2 yr mean	0.000	0.000	0.000	0.000	0.000	0.000	0.000			
Rain 3 yr mean	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
sunshine annual mean hr	0.000	0.000	0.016	0.000	0.000	0.032	0.000	0.000	0.000	
Wind vel annual mean (m/s)	0.00	0.00	0.01	0.00	0.00	0.03	0.92	0.06	0.00	0.00

Group: Okataina

Variable	TLI yr	TL-n yr	TL-p yr	TL-c yr	TL-s yr	SOI 1yr rolling	Rain annual (mm)	Rain 2 yr mean	Rain 3 yr mean	sunshine annual mean hr
TL-n yr	0.44									
TL-p yr	0.73	0.18								
TL-c yr	0.81	0.09	0.53							
TL-s yr	0.29	-0.09	-0.18	0.33						
SOI 1yr rolling	0.26	0.05	-0.12	0.46	0.34					
Rain annual (mm)	0.50	0.22	0.25	0.60	0.10	0.40				
Rain 2 yr mean	0.48	0.03	0.12	0.69	0.47	0.40	0.78			
Rain 3 yr mean	0.26	-0.11	-0.19	0.44	0.73	0.40	0.47	0.82		
sunshine annual mean hr	-0.35	0.09	-0.32	-0.47	0.05	-0.15	-0.78	-0.68	-0.38	
Wind vel annual mean (m/s)	-0.01	0.23	0.10	-0.06	-0.34	-0.17	-0.02	-0.18	-0.35	0.24

Significance (2-tailed t-test) of correlations (N = 136)

Variable	TLI yr	TL-n yr	TL-p yr	TL-c yr	TL-s yr	SOI 1yr rolling	Rain annual (mm)	Rain 2 yr mean	Rain 3 yr mean	sunshine annual mean hr
TL-n yr	0.000									
TL-p yr	0.000	0.033								
TL-c yr	0.000	0.289	0.000							
TL-s yr	0.001	0.307	0.038	0.000						
SOI 1yr rolling	0.002	0.529	0.170	0.000	0.000					
Rain annual (mm)	0.000	0.009	0.004	0.000	0.262	0.000				
Rain 2 yr mean	0.000	0.728	0.168	0.000	0.000	0.000	0.000			
Rain 3 yr mean	0.003	0.197	0.026	0.000	0.000	0.000	0.000	0.000		
sunshine annual mean hr	0.000	0.294	0.000	0.000	0.588	0.077	0.000	0.000	0.000	
Wind vel annual mean (m/s)	0.88	0.01	0.26	0.46	0.00	0.05	0.81	0.04	0.00	0.00

Table 4.5 b: Spearman correlation between variables (period 2009-2022)

Group: Rerewhakaaitu

Variable	TLI yr	TL-n yr	TL-p yr	TL-c yr	TL-s yr	SOI 1yr rolling	Rain annual (mm)	Rain 2 yr mean	Rain 3 yr mean	sunshine annual mean hr
TL-n yr	0.88									
TL-p yr	0.86	0.72								
TL-c yr	0.94	0.73	0.75							
TL-s yr	0.95	0.93	0.79	0.84						
SOI 1yr rolling	0.50	0.46	0.40	0.38	0.56					
Rain annual (mm)	0.49	0.21	0.45	0.59	0.38	0.42				
Rain 2 yr mean	0.69	0.46	0.69	0.71	0.60	0.41	0.79			
Rain 3 yr mean	0.76	0.63	0.79	0.66	0.71	0.43	0.47	0.83		
sunshine annual mean hr	-0.45	-0.08	-0.42	-0.59	-0.25	-0.18	-0.79	-0.70	-0.39	
Wind vel annual mean (m/s)	-0.39	-0.34	-0.44	-0.30	-0.32	-0.19	-0.02	-0.18	-0.34	0.24

Significance (2-tailed t-test) of correlations (N = 142)

Variable	TLI yr	TL-n yr	TL-p yr	TL-c yr	TL-s yr	SOI 1yr rolling	Rain annual (mm)	Rain 2 yr mean	Rain 3 yr mean	sunshine annual mean hr
TL-n yr	0.000									
TL-p yr	0.000	0.000								
TL-c yr	0.000	0.000	0.000							
TL-s yr	0.000	0.000	0.000	0.000						
SOI 1yr rolling	0.000	0.000	0.000	0.000	0.000					
Rain annual (mm)	0.000	0.011	0.000	0.000	0.000	0.000				
Rain 2 yr mean	0.000	0.000	0.000	0.000	0.000	0.000	0.000			
Rain 3 yr mean	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
sunshine annual mean hr	0.000	0.362	0.000	0.000	0.002	0.029	0.000	0.000	0.000	
Wind vel annual mean (m/s)	0.00	0.00	0.00	0.00	0.00	0.03	0.80	0.03	0.00	0.00

Group: Rotoehu

Variable	TLI yr	TL-n yr	TL-p yr	TL-c yr	TL-s yr	SOI 1yr rolling	Rain annual (mm)	Rain 2 yr mean	Rain 3 yr mean	sunshine annual mean hr
TL-n yr	0.94									
TL-p yr	0.85	0.69								
TL-c yr	0.96	0.93	0.76							
TL-s yr	0.85	0.87	0.58	0.87						
SOI 1yr rolling	-0.32	-0.45	-0.14	-0.37	-0.55					
Rain annual (mm)	0.29	0.31	0.21	0.28	0.14	0.43				
Rain 2 yr mean	0.32	0.28	0.27	0.29	0.22	0.41	0.81			
Rain 3 yr mean	0.24	0.17	0.21	0.19	0.19	0.42	0.52	0.83		
sunshine annual mean hr	-0.37	-0.39	-0.22	-0.36	-0.32	-0.19	-0.79	-0.71	-0.43	
Wind vel annual mean (m/s)	0.13	0.21	0.04	0.15	0.10	-0.21	-0.08	-0.21	-0.37	0.29

Significance (2-tailed t-test) of correlations (N = 139)

Variable	TLI yr	TL-n yr	TL-p yr	TL-c yr	TL-s yr	SOI 1yr rolling	Rain annual (mm)	Rain 2 yr mean	Rain 3 yr mean	sunshine annual mean hr
TL-n yr	0.000									
TL-p yr	0.000	0.000								
TL-c yr	0.000	0.000	0.000							
TL-s yr	0.000	0.000	0.000	0.000						
SOI 1yr rolling	0.000	0.000	0.107	0.000	0.000					
Rain annual (mm)	0.000	0.000	0.014	0.001	0.091	0.000				
Rain 2 yr mean	0.000	0.001	0.001	0.000	0.011	0.000	0.000			
Rain 3 yr mean	0.004	0.041	0.011	0.023	0.022	0.000	0.000	0.000		
sunshine annual mean hr	0.000	0.000	0.009	0.000	0.000	0.023	0.000	0.000	0.000	
Wind vel annual mean (m/s)	0.13	0.01	0.60	0.07	0.26	0.01	0.35	0.02	0.00	0.00

Group: Rotoiti

Variable	TLI yr	TL-n yr	TL-p yr	TL-c yr	TL-s yr	SOI 1yr rolling	Rain annual (mm)	Rain 2 yr mean	Rain 3 yr mean	sunshine annual mean hr
TL-n yr	0.63									
TL-p yr	0.75	0.44								
TL-c yr	0.70	0.68	0.23							
TL-s yr	0.65	0.21	0.60	0.35						
SOI 1yr rolling	0.11	0.16	-0.16	0.27	-0.20					
Rain annual (mm)	0.70	0.36	0.42	0.61	0.58	0.41				
Rain 2 yr mean	0.47	0.11	0.18	0.53	0.52	0.41	0.80			
Rain 3 yr mean	0.13	-0.18	-0.12	0.22	0.33	0.42	0.49	0.83		
sunshine annual mean hr	-0.66	-0.27	-0.31	-0.61	-0.53	-0.18	-0.80	-0.70	-0.40	
Wind vel annual mean (m/s)	0.07	0.17	0.38	-0.11	0.17	-0.18	-0.05	-0.19	-0.35	0.26

Significance (2-tailed t-test) of correlations (N = 145)

Variable	TLI yr	TL-n yr	TL-p yr	TL-c yr	TL-s yr	SOI 1yr rolling	Rain annual (mm)	Rain 2 yr mean	Rain 3 yr mean	sunshine annual mean hr
TL-n yr	0.000									
TL-p yr	0.000	0.000								
TL-c yr	0.000	0.000	0.006							
TL-s yr	0.000	0.011	0.000	0.000						
SOI 1yr rolling	0.193	0.049	0.054	0.001	0.018					
Rain annual (mm)	0.000	0.000	0.000	0.000	0.000	0.000				
Rain 2 yr mean	0.000	0.183	0.034	0.000	0.000	0.000	0.000			
Rain 3 yr mean	0.117	0.031	0.157	0.008	0.000	0.000	0.000	0.000		
sunshine annual mean hr	0.000	0.001	0.000	0.000	0.000	0.032	0.000	0.000	0.000	
Wind vel annual mean (m/s)	0.38	0.04	0.00	0.20	0.04	0.03	0.59	0.02	0.00	0.00

***Table 4.5 c**: Spearman correlation between variables (period 2009-2022)*

Group: Rotokakahi Outlet

Variable	TLI yr	TL-n yr	TL-p yr	TL-c yr	TL-s yr	SOI 1yr rolling	Rain annual (mm)	Rain 2 yr mean	Rain 3 yr mean	sunshine annual mean hr
TL-n yr	0.79									
TL-p yr	0.96	0.83								
TL-c yr	0.89	0.73	0.79							
TL-s yr	0.81	0.56	0.78	0.59						
SOI 1yr rolling	0.56	0.40	0.54	0.52	0.30					
Rain annual (mm)	0.20	0.41	0.19	0.42	-0.18	0.43				
Rain 2 yr mean	0.23	0.25	0.17	0.51	-0.24	0.36	0.80			
Rain 3 yr mean	0.11	-0.03	0.05	0.31	-0.26	0.28	0.49	0.81		
sunshine annual mean hr	-0.24	-0.46	-0.22	-0.49	0.04	-0.30	-0.80	-0.73	-0.46	
Wind vel annual mean (m/s)	-0.27	-0.04	-0.19	-0.29	-0.24	-0.30	-0.05	-0.18	-0.40	0.27

Significance (2-tailed t-test) of correlations (N = 114)

Variable	TLI yr	TL-n yr	TL-p yr	TL-c yr	TL-s yr	SOI 1yr rolling	Rain annual (mm)	Rain 2 yr mean	Rain 3 yr mean	sunshine annual mean hr
TL-n yr	0.000									
TL-p yr	0.000	0.000								
TL-c yr	0.000	0.000	0.000							
TL-s yr	0.000	0.000	0.000	0.000						
SOI 1yr rolling	0.000	0.000	0.000	0.000	0.001					
Rain annual (mm)	0.032	0.000	0.040	0.000	0.052	0.000				
Rain 2 yr mean	0.014	0.009	0.077	0.000	0.011	0.000	0.000			
Rain 3 yr mean	0.238	0.764	0.602	0.001	0.006	0.003	0.000	0.000		
sunshine annual mean hr	0.010	0.000	0.021	0.000	0.693	0.001	0.000	0.000	0.000	
Wind vel annual mean (m/s)	0.00	0.64	0.04	0.00	0.01	0.00	0.63	0.06	0.00	0.00

Group: Rotoma

Variable	TLI yr	TL-n yr	TL-p yr	TL-c yr	TL-s yr	SOI 1yr rolling	Rain annual (mm)	Rain 2 yr mean	Rain 3 yr mean	sunshine annual mean hr
TL-n yr	0.36									
TL-p yr	0.89	0.48								
TL-c yr	0.31	-0.18	-0.05							
TL-s yr	0.80	-0.06	0.60	0.38						
SOI 1yr rolling	-0.60	-0.24	-0.67	0.13	-0.44					
Rain annual (mm)	-0.21	-0.08	-0.14	-0.15	-0.22	0.42				
Rain 2 yr mean	-0.07	-0.19	-0.06	-0.07	0.04	0.41	0.80			
Rain 3 yr mean	-0.05	-0.21	-0.06	-0.12	0.25	0.40	0.49	0.83		
sunshine annual mean hr	0.19	0.11	0.03	0.38	0.25	-0.19	-0.80	-0.70	-0.41	
Wind vel annual mean (m/s)	0.20	0.27	0.19	0.13	-0.02	-0.15	-0.04	-0.18	-0.34	0.26

Significance (2-tailed t-test) of correlations (N = 140)

Variable	TLI yr	TL-n yr	TL-p yr	TL-c yr	TL-s yr	SOI 1yr rolling	Rain annual (mm)	Rain 2 yr mean	Rain 3 yr mean	sunshine annual mean hr
TL-n yr	0.000									
TL-p yr	0.000	0.000								
TL-c yr	0.000	0.029	0.555							
TL-s yr	0.000	0.498	0.000	0.000						
SOI 1yr rolling	0.000	0.005	0.000	0.116	0.000					
Rain annual (mm)	0.015	0.348	0.098	0.082	0.010	0.000				
Rain 2 yr mean	0.380	0.021	0.478	0.407	0.602	0.000	0.000			
Rain 3 yr mean	0.549	0.011	0.477	0.167	0.003	0.000	0.000	0.000		
sunshine annual mean hr	0.024	0.203	0.759	0.000	0.003	0.025	0.000	0.000	0.000	
Wind vel annual mean (m/s)	0.02	0.00	0.02	0.11	0.81	0.07	0.65	0.03	0.00	0.00

Group: Rotomahana

Variable	TLI yr	TL-n yr	TL-p yr	TL-c yr	TL-s yr	SOI 1yr rolling	Rain annual (mm)	Rain 2 yr mean	Rain 3 yr mean	sunshine annual mean hr
TL-n yr	0.41									
TL-p yr	0.76	0.01								
TL-c yr	0.79	0.34	0.31							
TL-s yr	0.45	0.16	0.06	0.48						
SOI 1yr rolling	0.22	0.28	-0.16	0.56	-0.03					
Rain annual (mm)	0.62	0.31	0.32	0.68	0.31	0.42				
Rain 2 yr mean	0.58	0.56	0.14	0.69	0.38	0.43	0.79			
Rain 3 yr mean	0.18	0.55	-0.32	0.44	0.34	0.43	0.49	0.83		
sunshine annual mean hr	-0.61	-0.07	-0.48	-0.58	-0.29	-0.18	-0.80	-0.70	-0.40	
Wind vel annual mean (m/s)	-0.17	0.08	0.08	-0.33	-0.34	-0.17	-0.05	-0.20	-0.35	0.26

Significance (2-tailed t-test) of correlations (N = 142)

Variable	TLI yr	TL-n yr	TL-p yr	TL-c yr	TL-s yr	SOI 1yr rolling	Rain annual (mm)	Rain 2 yr mean	Rain 3 yr mean	sunshine annual mean hr
TL-n yr	0.000									
TL-p yr	0.000	0.872								
TL-c yr	0.000	0.000	0.000							
TL-s yr	0.000	0.051	0.455	0.000						
SOI 1yr rolling	0.007	0.001	0.052	0.000	0.724					
Rain annual (mm)	0.000	0.000	0.000	0.000	0.000	0.000				
Rain 2 yr mean	0.000	0.000	0.099	0.000	0.000	0.000	0.000			
Rain 3 yr mean	0.034	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
sunshine annual mean hr	0.000	0.425	0.000	0.000	0.001	0.033	0.000	0.000	0.000	
Wind vel annual mean (m/s)	0.04	0.32	0.35	0.00	0.00	0.04	0.53	0.02	0.00	0.00

***Table 4.4 d**: Spearman correlation between variables (period 2009-2022)*

Group: Rotorua

Variable	TLI yr	TL-n yr	TL-p yr	TL-c yr	TL-s yr	SOI 1yr rolling	Rain annual (mm)	Rain 2 yr mean	Rain 3 yr mean	sunshine annual mean hr
TL-n yr	0.31									
TL-p yr	0.90	0.17								
TL-c yr	0.81	0.21	0.58							
TL-s yr	0.87	0.13	0.83	0.66						
SOI 1yr rolling	0.17	0.22	-0.02	0.43	0.07					
Rain annual (mm)	0.04	0.50	-0.17	0.25	-0.21	0.41				
Rain 2 yr mean	-0.18	0.51	-0.43	0.14	-0.37	0.40	0.80			
Rain 3 yr mean	-0.32	0.29	-0.52	0.01	-0.39	0.41	0.48	0.83		
sunshine annual mean hr	-0.13	-0.59	0.11	-0.24	0.01	-0.16	-0.79	-0.70	-0.40	
Wind vel annual mean (m/s)	-0.18	-0.06	0.06	-0.31	-0.29	-0.17	-0.03	-0.18	-0.34	0.23

Significance (2-tailed t-test) of correlations (N = 141)

Variable	TLI yr	TL-n yr	TL-p yr	TL-c yr	TL-s yr	SOI 1yr rolling	Rain annual (mm)	Rain 2 yr mean	Rain 3 yr mean	sunshine annual mean hr
TL-n yr	0.000									
TL-p yr	0.000	0.040								
TL-c yr	0.000	0.012	0.000							
TL-s yr	0.000	0.117	0.000	0.000						
SOI 1yr rolling	0.047	0.009	0.855	0.000	0.403					
Rain annual (mm)	0.637	0.000	0.038	0.003	0.013	0.000				
Rain 2 yr mean	0.029	0.000	0.000	0.091	0.000	0.000	0.000			
Rain 3 yr mean	0.000	0.001	0.000	0.920	0.000	0.000	0.000	0.000		
sunshine annual mean hr	0.127	0.000	0.204	0.004	0.940	0.059	0.000	0.000	0.000	
Wind vel annual mean (m/s)	0.04	0.52	0.51	0.00	0.00	0.04	0.77	0.04	0.00	0.01

Group: Tarawera

Variable	TLI yr	TL-n yr	TL-p yr	TL-c yr	TL-s yr	SOI 1yr rolling	Rain annual (mm)	Rain 2 yr mean	Rain 3 yr mean	sunshine annual mean hr
TL-n yr	0.51									
TL-p yr	0.74	0.20								
TL-c yr	0.60	0.33	0.20							
TL-s yr	0.34	0.13	-0.15	0.36						
SOI 1yr rolling	-0.32	-0.05	-0.38	0.12	-0.21					
Rain annual (mm)	0.24	0.22	0.35	0.21	-0.37	0.39				
Rain 2 yr mean	0.18	0.00	0.22	0.22	-0.10	0.40	0.80			
Rain 3 yr mean	-0.16	-0.15	-0.25	0.05	0.12	0.44	0.49	0.83		
sunshine annual mean hr	-0.45	-0.23	-0.53	-0.13	0.19	-0.16	-0.79	-0.71	-0.39	
Wind vel annual mean (m/s)	-0.05	0.06	0.10	-0.05	-0.21	-0.21	-0.04	-0.19	-0.34	0.25

Significance (2-tailed t-test) of correlations (N = 137)

Variable	TLI yr	TL-n yr	TL-p yr	TL-c yr	TL-s yr	SOI 1yr rolling	Rain annual (mm)	Rain 2 yr mean	Rain 3 yr mean	sunshine annual mean hr
TL-n yr	0.000									
TL-p yr	0.000	0.019								
TL-c yr	0.000	0.000	0.018							
TL-s yr	0.000	0.135	0.077	0.000						
SOI 1yr rolling	0.000	0.570	0.000	0.158	0.016					
Rain annual (mm)	0.004	0.010	0.000	0.012	0.000	0.000				
Rain 2 yr mean	0.036	0.999	0.010	0.011	0.266	0.000	0.000			
Rain 3 yr mean	0.063	0.088	0.004	0.567	0.149	0.000	0.000	0.000		
sunshine annual mean hr	0.000	0.006	0.000	0.144	0.026	0.056	0.000	0.000	0.000	
Wind vel annual mean (m/s)	0.54	0.50	0.23	0.57	0.01	0.01	0.66	0.03	0.00	0.00

Group: Tikitapu

Variable	TLI yr	TL-n yr	TL-p yr	TL-c yr	TL-s yr	SOI 1yr rolling	Rain annual (mm)	Rain 2 yr mean	Rain 3 yr mean	sunshine annual mean hr
TL-n yr	0.42									
TL-p yr	0.35	-0.23								
TL-c yr	0.86	0.24	0.21							
TL-s yr	0.88	0.42	0.07	0.66						
SOI 1yr rolling	-0.31	-0.44	0.02	-0.31	-0.27					
Rain annual (mm)	-0.11	-0.06	0.33	-0.09	-0.35	0.38				
Rain 2 yr mean	-0.12	-0.27	0.39	-0.03	-0.39	0.37	0.81			
Rain 3 yr mean	-0.21	-0.38	0.10	0.00	-0.37	0.40	0.49	0.82		
sunshine annual mean hr	0.09	-0.04	-0.44	0.10	0.36	-0.15	-0.79	-0.72	-0.41	
Wind vel annual mean (m/s)	0.01	0.11	-0.18	-0.02	0.06	-0.21	-0.05	-0.21	-0.37	0.26

Significance (2-tailed t-test) of correlations (N = 135)

Variable	TLI yr	TL-n yr	TL-p yr	TL-c yr	TL-s yr	SOI 1yr rolling	Rain annual (mm)	Rain 2 yr mean	Rain 3 yr mean	sunshine annual mean hr
TL-n yr	0.000									
TL-p yr	0.000	0.008								
TL-c yr	0.000	0.005	0.014							
TL-s yr	0.000	0.000	0.450	0.000						
SOI 1yr rolling	0.000	0.000	0.840	0.000	0.001					
Rain annual (mm)	0.214	0.510	0.000	0.306	0.000	0.000				
Rain 2 yr mean	0.173	0.002	0.000	0.721	0.000	0.000	0.000			
Rain 3 yr mean	0.017	0.000	0.273	0.956	0.000	0.000	0.000	0.000		
sunshine annual mean hr	0.307	0.642	0.000	0.234	0.000	0.080	0.000	0.000	0.000	
Wind vel annual mean (m/s)	0.90	0.19	0.04	0.86	0.47	0.01	0.55	0.02	0.00	0.00

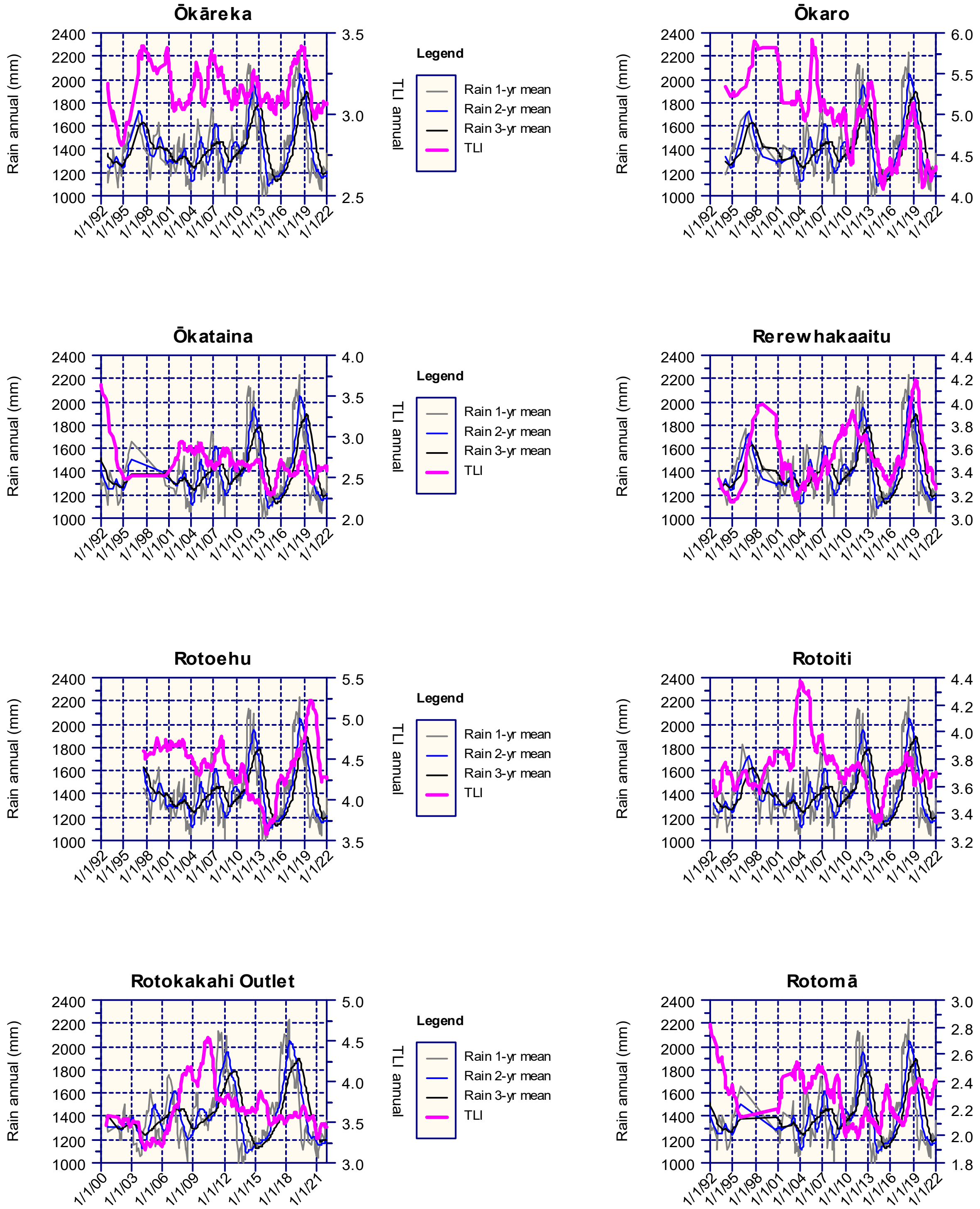


***Figure 4.4 a**: Time series of annualised TLI and annualised rainfall over time.*

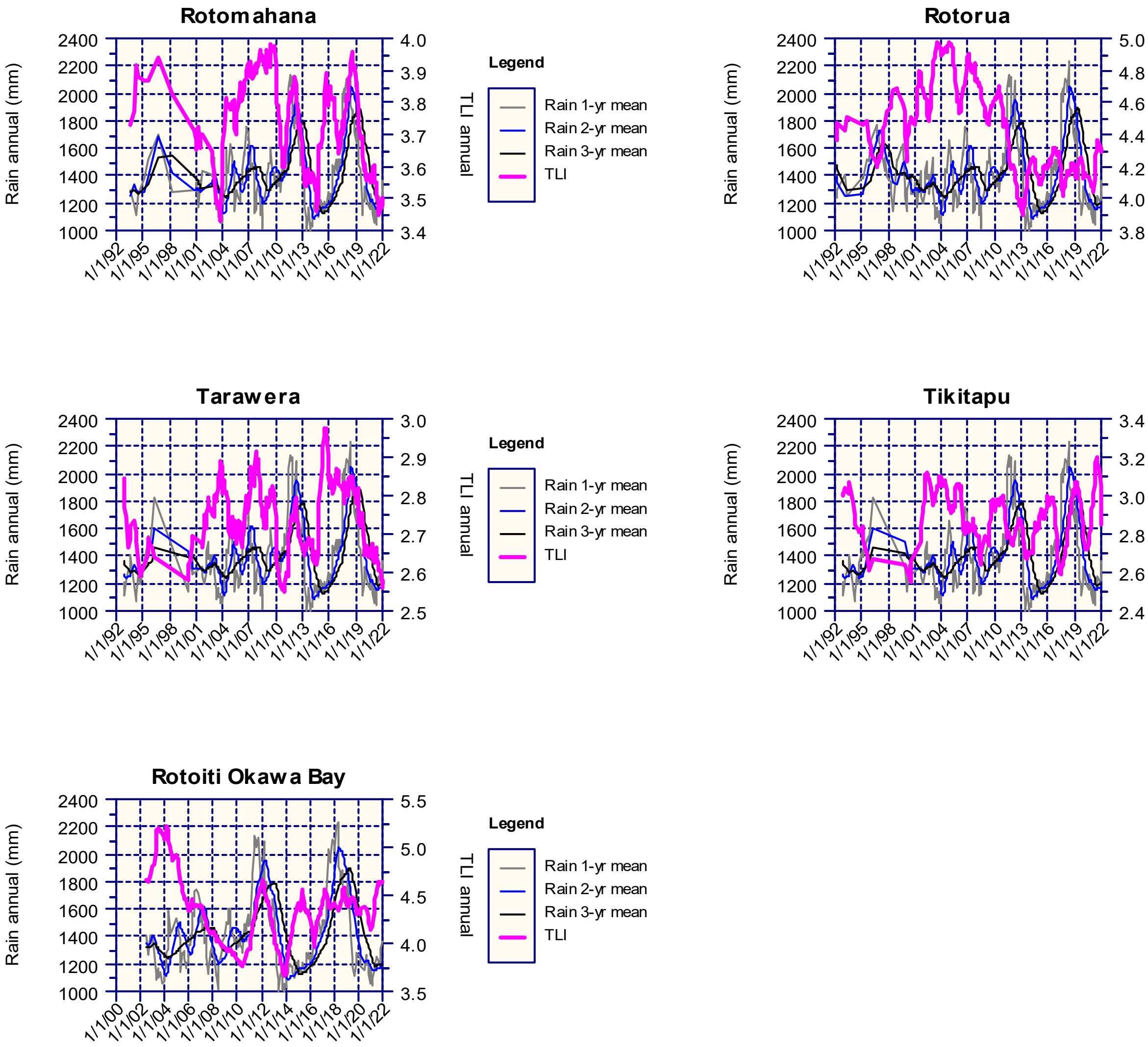


***Figure 4.4 a**: Time series of annualised TLI and annualised rainfall over time.*

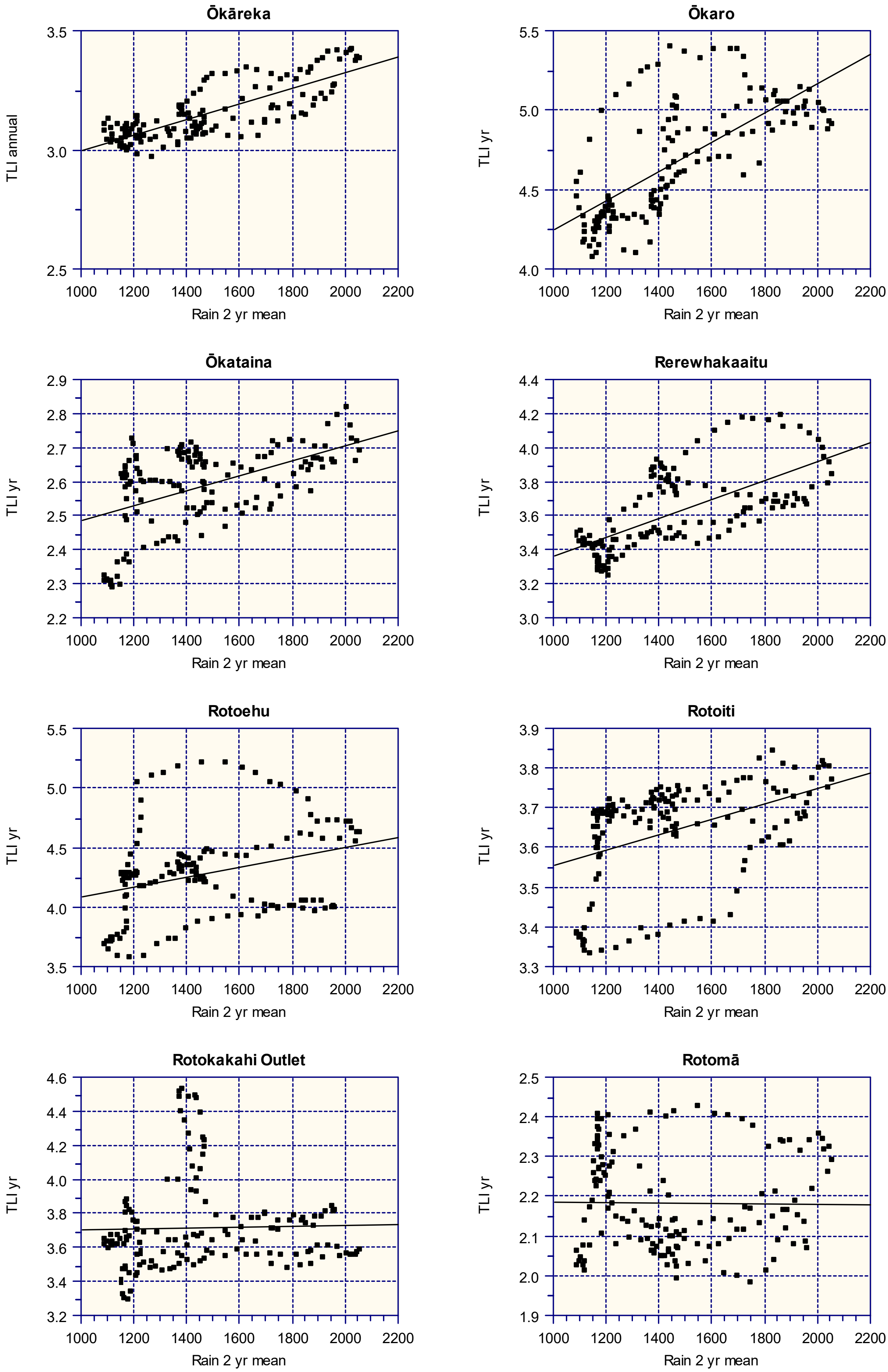


***Figure 4.5 a**: Relationship between annualised TLI and annualised rainfall over time.*

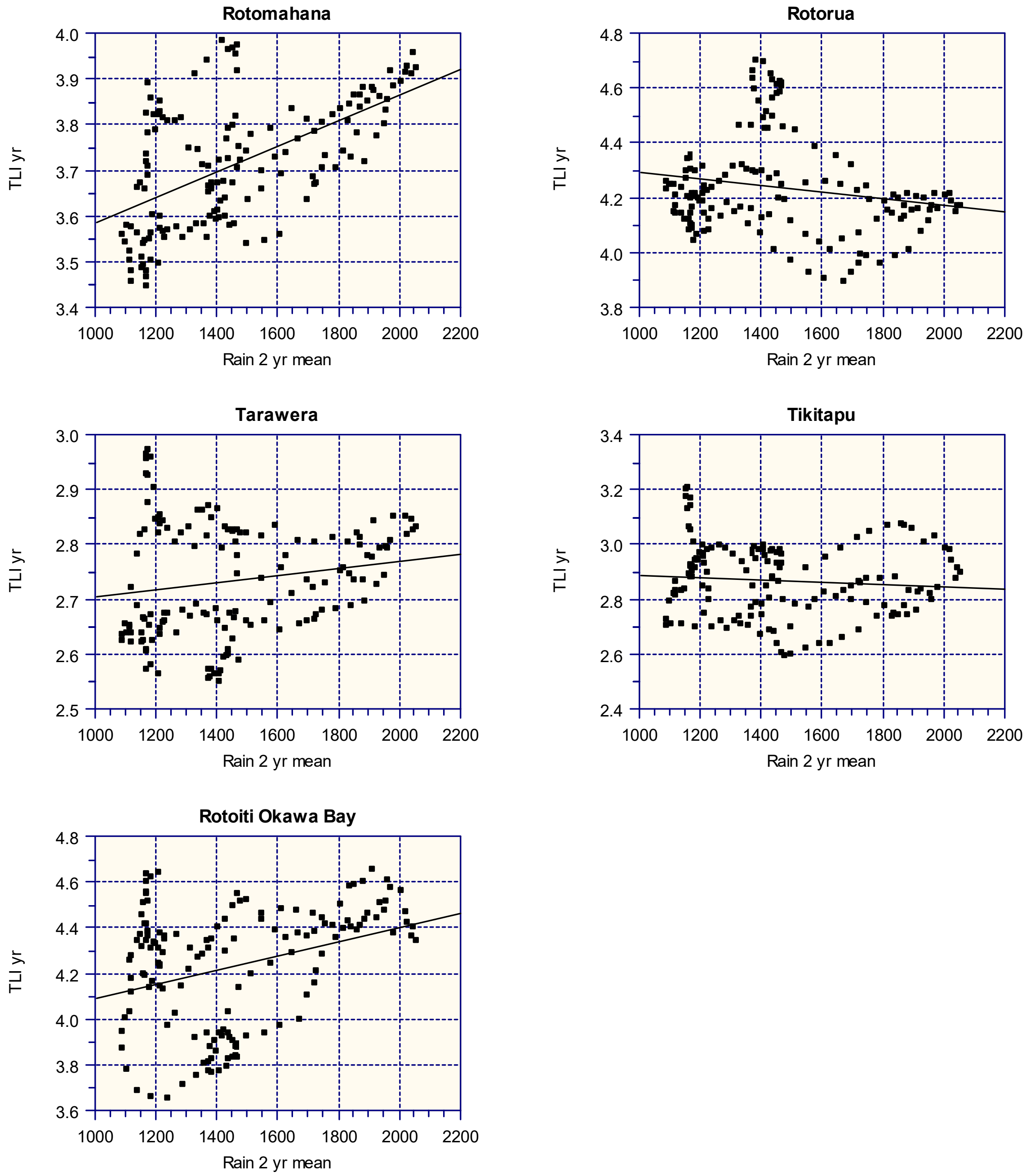


***Figure 4.5 b**: Relationship between annualised TLI and annualised rainfall over time.*

Previous studies have found that large scale climate variables such as the SOI are strongly associated water quality trends and can overwhelm the ability to detect a signal of landuse change (Snelder et al. 2021), but these relationships are complex. In any lake, many internal and external factors drive changes in water quality including nutrient and sediment inputs, climate, changes in aquatic plant biomass. The interannual variability in the composition of algae species is itself an intrinsic property of multi-species communities in seasonal environments, and variability can arise without interannual variability of external conditions (Dakos et al. 2009).

4.4 Review of TLI targets

The TLI targets set in the RNRP were based on achieving historical water quality conditions. For Lake Rotorua this was based on achieving water quality state that existed in the 1960's; while for the other Rotorua lakes the target was equivalent to water quality in the early 1990's. In some cases, the TLI target was pragmatically based on achieving a 'realistic' improvement (i.e. Lake Ōkaro). The background on how the TLI targets were set is described in a memo by Lee (2013) and summarised in **Table 4.5**.

For many lakes, the TLI targets were based on the TLI during 1993/94 to 1994/95. The rainfall at this time was relatively low compared the long term. This suggests that the TLI targets were based on a period when interannual variability in the TLI may have been moderately low.

Abell (2018) and Abell et al. (2020) have modelled lake 'natural state' conditions for TP, TN and TLI. Although the TLI targets are not intended to reflect 'natural state' conditions, they can be used as another line of evidence to test if the lake TLI targets are realistic. The modelled natural state TLI are considerably less than the TLI targets for lakes (in order of the difference): Ōkaro (2 units), Rotorua (1.3 units), Rotomahana (1.2 units), Rotoiti (0.9 units), Rotoehu (0.8 units) (**Table 4.3**). For Ōkaro, Rotorua and Rotomahana the current state is also less than or equal to the targets – which suggests that the current targets may be too lenient.

An important aim of the TLI target is to sufficiently improve water quality so as to avoid excessive phytoplankton blooms. Using an annual TLI does not always detect occasional summer algae blooms because the score is averaged over multiple months and variables. This is one reason that the NPS-FM uses both an annual median and a maximum statistic for the chlorophyll-*a* attribute. In the last three years, two lakes have exceeded the NPS-FM bottom-line value of 60 mg/m^3 for chlorophyll-a maximum, these were Lake Ōkaro and Lake Rotoehu (see section 3). At the time of these algae blooms Lake Rotoehu was not meeting its TLI target, but Lake Ōkaro was meeting its target. Over the last 15 years, this pattern of meeting the annual TLI target of 5.0 while still having intensive summer algae blooms (exceeding the NPS-FM bottom-line), has occurred nine times in Lake Ōkaro[3], but does not occur in the other Te Arawa Lakes (**Figure 4.6**). This is another line of evidence suggesting that the current TLI target for Lake Ōkaro on 5.0 may be too lenient. More work is needed to determine a revised TLI target consistent with the lake meeting the NPS-FM bottom-line value for maximum chlorophyll-*a*; however, based on past events, a revised target would likely need to be about 4.4 or less.

[3] This occurred during spring / early summer of 2008, 2010, 2011, 2016, 2017 and 2021.

Table 4.5: TLI targets for the Rotorua Lakes, their basis from Lee (2013) and modelled Natural State from Abell et al. (2020).

Lake	TLI Target	Natural State[1] TLI (CI)	Target TLI rational [2]	TLI (2019-2021)	trophic
Ōkāreka	3.0	2.8 (2.5-3.2)	1993/94 TLI	3.1	mesotrophic
Ōkaro	5.0	3.0 (2.5-3.4)	A "realistic" improvement from *c*. 2000 TLI	4.6	eutrophic
Ōkataina	2.6	2.8 (2.4-3.2)	1993/94 TLI	2.6	oligotrophic
Rerewhakaaitu	3.6	3.4 (2.9-3.9)	> 1993/94 TLI allows for "nautal" variations	3.7	mesotrophic
Rotoehu	3.9	3.1 (2.6-3.6)	1990/91 TLI - good years	4.7	eutrophic
Rotoiti	3.5	2.6 (2.0-3.1)	< 1993/94 TLI	3.7	mesotrophic
Rotokakahi	3.1	3.1 (2.7-3.5)	1993/94 TLI	3.5	mesotrophic
Rotomā	2.3	2.7 (2.2-3.1)	1993/94 TLI	2.4	oligotrophic
Rotomahana	3.9	2.7 (2.3-3.2)	1993/94 TLI	3.6	mesotrophic
Rotorua	4.2	2.9 (2.5-3.4)	1960's TLI prior to sewage	4.2	eutrophic
Tarawera	2.6	2.7 (2.3-3.2)	1994/95 TLI	2.7	oligotrophic
Tikitapu	2.7	3.0 (2.6-3.5)	1993/94 TLI	3.0	oligotrophic

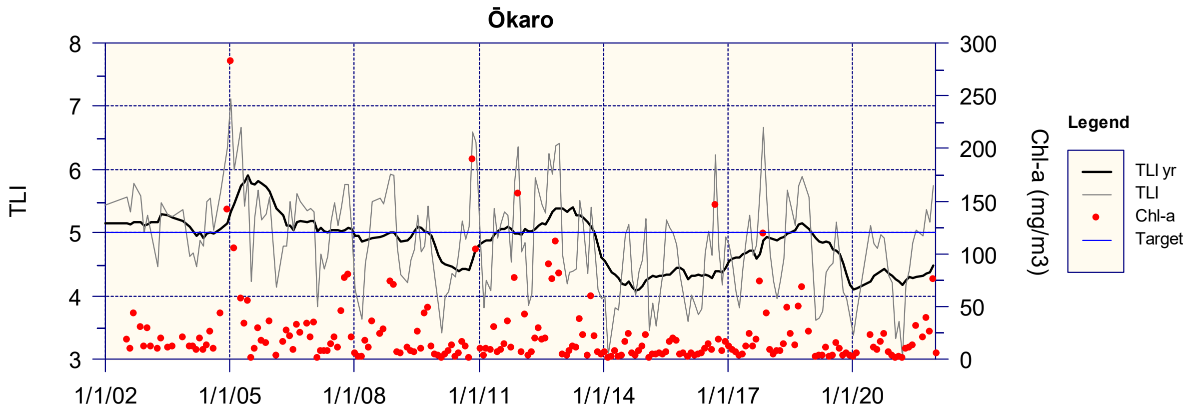


Figure 4.6 a: Rolling annual TLI compared the TLI target and monthly chlorophyll-a measurements in Lake Ōkaro, showing high values of chlorophyll-*a* (>60 mg/m^3) even when the annual TLI is below its target.

5. Conclusion

TP results from the period August 2010 to September 2019 (inclusive) were higher in many lakes due to additive interface in the laboratory method by silica and arsenic. A new laboratory method was adopted in October 2019 to address these issues. Lake specific formula have been developed to correct data during the period when analysis was potentially biased. However, for some lakes, the corrected dataset will still have apparent variation in TP results caused by interannual and seasonal variations in Si.

Eight lakes exceed their TLI targets for the 3-year period ending July 2021 (plus Rotoiti Okawa Bay), however only four lakes currently exceed the requirements in the RNRP for setting Action Plans (i.e. the 3-year moving average TLI exceeds its target TLI by 0.2 for two consecutive years); these lakes are: Lakes Rotoehu, Rotoiti, Rotokakahi and Tikitapu.

Trend analysis over the last 12-year time period found two lakes (Rerewhakaaitu, Rotokakahi outlet) with decreasing (improving) TLI and three lakes (Rotoehu, Rotoiti Okawa Bay and Rotomā) with increasing (worsening) TLI**.** Trend analysis over the long term found seven lakes with decreasing TLI and one lake with increasing TLI. Lakes that had a "very likely" decrease (improvement) in all TLI variables (TL-n, TL-p, TL-c, TL-s) over the long term were: Ōkaro, Ōkataina, and Rotorua.

The use of a uniform 0.2 TLI-unit tolerance is within the 95th percentile range of interannual variability in oligotrophic lakes, and thus provides a reasonable estimate of interannual variability in the absence of eutrophication. For eutrophic lakes, the interannual variability is considerably higher than 0.2 TLI-units but increasing the tolerance to match interannual variability in eutrophic lakes would risk entrenching periodically poor water quality as part of the lake target. Rather than increase the tolerance, a more robust approach to account for interannual variability is to uses statistical tests over consecutive time periods (e.g., 5-year intervals), and to interpret short term changes in TLI in the context of variation occurring in other lakes and due to climatic factors.

Lakes that have a correlation in the interannual variation of their TLI values might be used as a psedo-control to help test if periods of variation in TLI might be due to catchment specific anthropogenic influence as compared to influence from climatic variation or large scale landuse changes. The lakes that most frequently had significant correlations in TLI with other lakes were Lakes Rotomā and Ōkataina. Strong correlation in TLI was found between the lakes: Rotorua, Rotoiti, Rotomā and Ōkataina. This approach can be use with more confidence when the lakes being used as a control do not have a direct hydrological connection, but still should only be viewed as one of multiple lines of evidence from which to draw conclusions.

There may also be potential for adjusting the expression of the TLI to better account for interannual variability in TLI caused by climatic conditions. Several climatic variables correlated with the interannual variability of TLI in the Te Arawa Lakes, but no single climatic variable had good correlations with TLI in all of the lakes. The climatic variable that correlated with best with most lakes was the two-year average rainfall and the southern oscillation index.

For Lake Ōkaro, consideration could be given to setting a lower (stricter) TLI target to better ensure that ensure that algae blooms do not exceed the NPS-FM bottom-line values.

References

Abell JM, van Dam-Bates P, Özkundakci O, Hamilton DP (2020) Reference and current trophic level index of New Zealand lakes: benchmarks to inform lake management and assessment. New Zealand Journal of Marine and Freshwater Research 54: 636-657, doi: 10.1080/00288330.2020.1726974

Ballantine, D., Booker, D., Unwin, M., and Snelder, T. 2010. *Analysis of national river water quality data for the period 1998–2007*. NIWA Client Report: CHC2010-038 for Ministry for the Environment (Project MFE10502): sec. 2.4.3.

Burns N.; Bryers G.; Bowman E. 2000. Protocol for monitoring trophic levels of New Zealand lakes and reservoirs. Prepared for Ministry of the Environment by Lakes Consulting, March 2000. Web: http://www.mfe.govt.nz/publications/water/protocol-monitoring-trophic-levelsmar-2000/index.html

Burns, N.M.; McIntosh J.; Scholes P. 2005. Strategies for managing the lakes of the Rotorua District, New Zealand. *Lake Reserv. Manage. 21*(1):61–72.

Burns NM, McIntosh J, Scholes P 2009. Managing the lakes of the Rotorua District, New Zealand. *Lake and Reservoir Management 25*:284-296.

Davies-Colley RJ, McBride G 2016. Accounting for changes in method in long-term nutrient data. Recommendations based on analysis of paired SoE data from Wellington rivers. Prepared for the Ministry for the Environment by NIWA. NIWA Client Report No: HAM2016-070

Davies-Colley RJ, Hughes AO, Verburg P, Storey R. 2012. *National Environmental Monitoring and Reporting (NEMaR) Variables Step 2*. Prepared for the Ministry for the Environment by NIWA. NIWA Client Report HAM2021-092

Dakos V, Beninca E, van Nes EH, Philippart CJM, Scheffer M 2009. Interannual variability in species composition explained as seasonally entrained chaos. Proceedings of the Royal Society Bioloigical Sciences.

Hamill K.D., Scholes P. 2016. *Rotorua Te Arawa Lakes State and trends to 2014/15*. Prepared for Bay of Plenty Regional Council.

Hamill KD, Kelly D, Hamilton D, Howard-Williams C, Robertson B, Schallenberg M, Vant B, Ward N. 2014. *Attributes for Intermittently Open and Closed Lakes and Lagoons (ICOLLs) applicable to the National Objectives Framework for Fresh Water*. Prepared for Ministry for the Environment.

Helsel, D.R. and R.M. Hirsch. 1992. *Statistical Methods in Water Resources*, Elsevier, NY.

Hirsch R.M., Slack J.R. 1984. A non-parametric trend test for seasonal data with serial dependence. *Water Resources Research 20*(6): 727-732.

Husdon, N.; Ballantine, D.; Gibbs, M.; de Winton, M.; Storey, R.; Verburg, P.; Hamill, K.D. (2011). *Investigation of single indicators for water quality assessment and reporting.* Prepared for Ministry for the Environment. NIWA Client Report HAM2011-066.

Intergovernmental Panel on Climate Change (IPCC) 2013. *Climate change 2013: The physical science basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [TF Stocker, D Qin, G-K Plattner, MMB Tignor, SK Allen, J Boschung, … PM Midgley (Eds)]. Cambridge and New York: Cambridge University Press. doi:10.1017/CBO9781107415324

Jowett, I. 2018.TimeTrends. v.6.30 2017. Trends and Equivalent Analysis. Funded by FRST Envirolink and sponsorship from Northland Regional Council, Hawke's Bay Regional Council, Southland Regional Council and Auckland Council.

Larned, S., Snelder, T., Unwin, M., McBride, G., Verburg, P., and McMillan, H. 2015. *Analysis of water quality in New Zealand lakes and rivers.* NIWA client report: CHC2015-033. Prepared for Ministry for the Environment.

Larned, S., T. Snelder, M. Unwin, and G. McBride, 2016. Water Quality in New Zealand Rivers: Current State and Trends. *New Zealand Journal of Marine and Freshwater Research 50*:389–417.

Larned S, Hudson N, & McBride, G 2018. *Water quality state and trends in New Zealand rivers. Analyses of national data ending in 2017*. Prepared for Ministry for the Environment. NIWA Client Report No: 2018347CH.

Lee M 2013. Trophic level indices for Rotorua Lakes. Memorandum to Bay of Plenty Regional Council Strategy, Policy and Planning Committee. 14 February 2013. File Ref. 4.000867, 8.00139

McBride G.B 2005. Statistical Methods for Water Quality Management, Issues, Problems and Solutions. John Wiley & Sons Inc.

McBride GB 2019. Has water quality improved or been maintained? A quantitative assessment procedure. *Journal of Environmental Quality,* 48:412-420 https://doi.org/10.2134/jeq2018.03.0101

McBride, G.B., Cole, R., Westbrooke, I., and Jowett, I.G. 2014. Assessing environmentally significant effects: A better strength-of-evidence than a single P value? Environmental Monitoring and Assessment, 186: 2729–2740.

McBride, C.G., Abell, J.M., and Hamilton, D.P. 2018. *Long-term nutrient loads and water quality for Lake Rotorua: 1965 to 2017*. ERI report 123. Environmental Research Institute, The University of Waikato, Hamilton, New Zealand. 70 pp.

Morgenstern U., C. J. Daughney G. Leonard D. Gordon F. M. Donath, R. Reeves. 2015. Using groundwater age and hydrochemistry to understand sources and dynamics of nutrient contamination through the catchment into Lake Rotorua. *New Zealand. Hydrology and Earth System Sciences 18:* 803–822.

NEMS 2019. National Environmental Monitoring Standards: Water Quality. Part 3 of 4: Sampling, Measuring, Processing and Archiving of Discrete River Water Quality Data. Version 1.0.0. http://www.nems.org.nz

New Zealand Government 2020. National Policy Statement for Freshwater Management 2014 (amended 2020).

Rus, D.L., Patton, C.J., Mueller, D.K. and Crawford, C.G. (2012) Assessing total nitrogen in surface-water samples - precision and bias of analytical and computational methods. US Geological Survey Scientific Investigations Report, 2012-5281: 38.

Schallenberg M. 2014. *Determining the reference condition of New Zealand lakes*. Science for Conservation Series. Prepared for Department of Conservation by Hydrosphere Research Ltd.

Schallenberg M, van der Zon KA 2021. *Review of lake Trophic Level Index*. Prepared for the Regional Council Lakes Focus Group September 2020 (revised March 2021). University of Otago, Dunedin

Scarsbrook M. (2006): *State and trends in the National River Water Quality Network (1989-2005).* NIWA Client Report HAM2006-131 to Ministry for the Environment.

Snelder, T. 2018. *Assessment of recent reductions in E.coli and sediment in rivers of the Manawatū-Whanganui region*. LWP Client Report for Horizons Regional Council and the Ministry for the Environment.

Snelder T, Fraser C 2018. *Aggregating Trend Data for Environmental Reporting*. LWP Client Report 2018-01. Prepared for the Ministry for the Environment.

Snelder T, Fraser C 2018b. *LWP-Trends library Version 1811: LWPTrends_v1811.r.* LWP Ltd Report, p34, December 2018

Stephens, T., Hamill K.D., McBride C. 2018. Lake Rotorua: Trends in Water quality (2001-2017). Technical report produced for Lake Rotorua Technical Advisory Group.

Stocker, T., D.Q. Qin, and G.-K. Plattner (Editors). 2014. *Climate Change 2013: The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Verburg, P., Hamill, K.D., Unwin, M., Hamilton, D. (2010). *Lake water quality in New Zealand 2010: Status and trends.* Prepared for Ministry for the Environment by NIWA, Opus International Consultants and University of Waikato.

Appendices

Appendix A – Laboratory Analysis Methods and Changes

Table A1.1 *Current methods used for chemical/biological analysis of water samples*

Parameter (abbreviation)	**Method**	**Detection Limit/ Units**
Ammonium Nitrogen (NH_4-N)	Phenyl/hypochlorite colorimetry. FIA APHA 4500-NH3 G.	1 mg/m^3
Total Oxidised Nitrogen (NOx)	Flow injection analyser. APHA 4500 NO3-I	1 mg/m^3
Total Nitrogen (TN)	Persulphate digestion, auto cadmium reduction. FIA	
Total Phosphorus (TP)	Acid persulphate digestion, molybdate colorimetry. FIA. Apha 4500-P H	1 mg/m^3
Dissolved Reactive Phosphorus (DRP)	Molybdenum blue colorimetry, FIA, APHA 4500-P G.	1 mg/m^3
Water clarity – Secchi disc	Secchi disc visibility measured in metres (to 0.1m increments) with a viewing tube.	0.1 m
Turbidity	APHA Method 2130B-HACH 2100N ratio and signal averaging on.	0.01 NTU
pH	APHA method 4500-H+ measurement at 25^{o}C	
Temperature	Seabird 19Plus or 19PlusV2 CTD	0.1 deg C
Electrical conductivity	Seabird 19Plus or 19PlusV2 CTD	0. 05 µS/m
Dissolved oxygen	Seabird 19Plus or 19PlusV2 CTD (accuracy 2% of saturation)	
PAR Light Sensor	Biospherical QSP-2300	µmol photons/m^2.s
Escherichia coli (E.coli)	Membrane filtration, Standard Methods for the Examination of Water & Wastewaters (2005)	1 cfu/100ml

Table A1.2: *Historical laboratory method changes of TN, TP and DRP*

Internal Method Ref:	Date in use	Description	Lab	Detection Limit (g/m^3)
TKN-1	Up to Oct 08	APHA Method 4500B NIWA mod., Oct 1990	BOPRC (EBOP)	0.09 (mostly recorded as actual values)
TKN-7	Oct 08 – Oct 09 (some intermittent use 05/06	Kjeldahl Digestion. Phenol/hypchlorite colorimetry (discrete Analyser) APHA 4500-Norg C (modified)	RJH	0.1
TN-2	Project use 92	Persulphate digestion, AA hydrazine reduction	NIWA	0.001
TN-5	Nov 09 – present NIWA (intermittent 05/06)	Persulphate digestion, auto cadmium reduction. FIA	BOPRC (20.08.10) NIWA	0.001
TP-1	Up to July 08	NWASCO Misc Pub. No38, 1982 Antimony – Phosphate Molybdate, derived Murphy-Riley Method (1962)	BOPRC (EBOP)	*listed as* 0.008 recorded as 0.001
TP-6	Aug 08 – Oct 09	Total phosphorus digestion, ascorbic acid colorimetry. Discrete Analyser. Apha 4500-P E(modified)		0.004
TP-2	Nov 09 – Aug 10	Acid persulphate digestion/ molybdenum blue colorimetry	NIWA	0.001
TP-5	Aug 10 – Sept 2019	Acid persulphate digestion, molybdate colorimetry. FIA. Apha 4500-P H	BOPRC (20.08.10)	0.001
TP	Oct 2019 - present	Acid persulphate digestion, molybdate colorimetry. FIA. Apha 4500-P H New channel	BOPRC (Oct 2019)	0.001
DRP-1	Up to Sept 08	NWASCO Misc Pub. No38, 1982 Antimony – Phosphate Molybdate, derived Murphy-Riley Method (1962)	BOPRC (Env. BOP)	*historically listed as* 0.004 recorded as 0.001
DRP-6	Oct 08 – Oct 09	Molybdenum blue colorimetry, discrete analyser, APHA 4500 P – E (Modified)	Hills	0.004
DRP-5	Nov 09 – Aug 10	Molybdenum blue colorimetry, FIA, APHA 4500-P G.	NIWA (08.12.09)	0.001
DRP-5	Aug 10 – Sept 2019	Molybdenum blue colorimetry, FIA, APHA 4500-P G.	BOPRC (20.08.10)	0.001
DRP	Oct 2019 - present	Molybdenum blue colorimetry, FIA, APHA 4500-P G. new channel	BOPRC (Oct 2019)	0.001

Appendix B – Adjusting for changes in laboratory analysis of total nitrogen and total phosphorus

Introduction

Changes in laboratory methods for analysing total nitrogen (**TN**), total phosphorus (**TP**) and dissolved reactive phosphorus (DRP) occurred between late 2008 and 2010 (**Appendix A**). These analytical changes resulted in lower detection limits and less variability of results. However, the analytical changes also appeared to cause a step change decrease in TN results and a step change increase in TP (**Figure B.1**). This complicated the assessment of water quality trends and caused uncertainty when reporting current state.

No cross-calibration between the two laboratory methods had been undertaken, which made it difficult to accurately quantify differences between the methods. Scholes and Hamill (2016) developed a generic TP correction factor using a statistical approach, to account for the step-change. However, subsequent work has allowed for more accurate, lake-specific corrections, as described below.

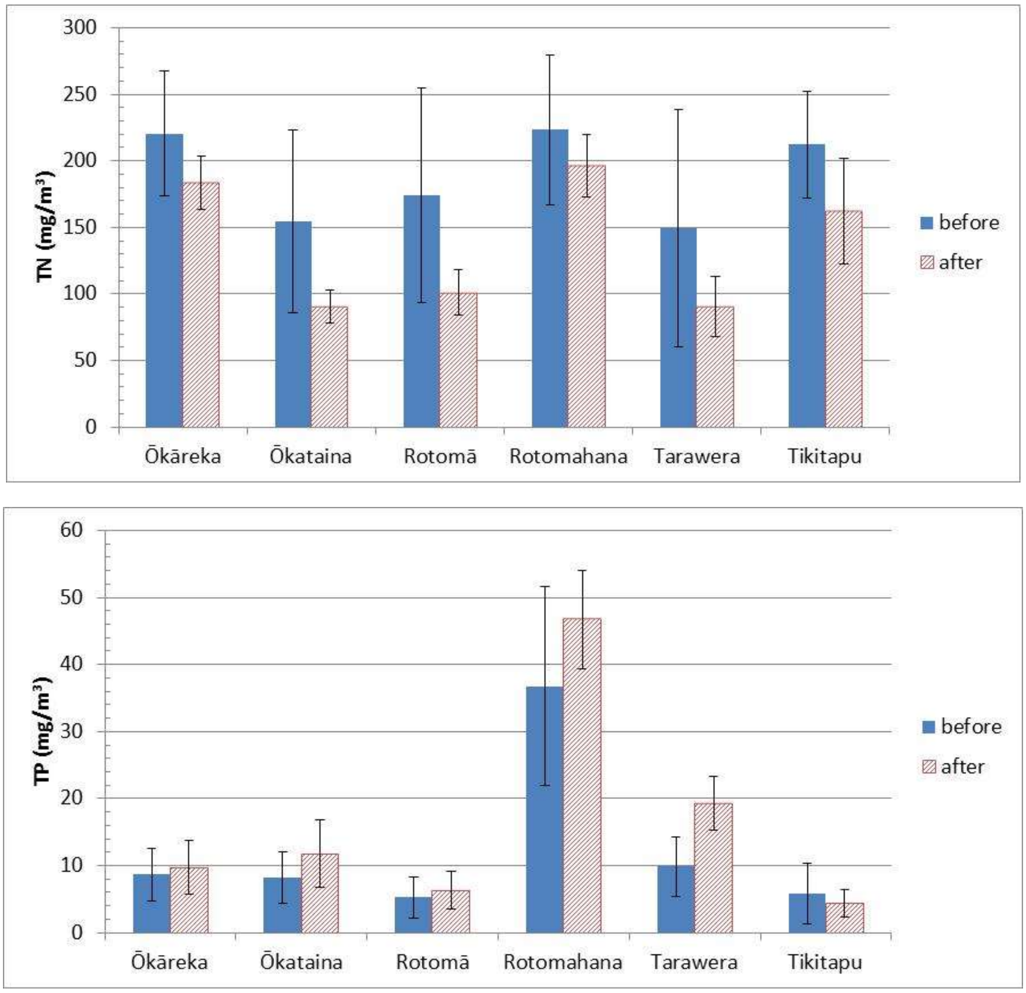


***Figure B.1**: Comparison of average TN (top graph) and TP (bottom graph) results for the four-year period before July 2009 and after July 2010. Selection of Rotorua lakes limited to those with few pressures and no apparent trends in TN or TP for the 5-year period before July 2008 and the five years after January 2010. Error bars are one standard deviation.*

Phosphorus

In 2017 /2018 BOPRC laboratory undertook inter-laboratory comparisons of TP and DRP in Lake Tarawera. This found the BOPRC laboratory reading higher results than the Hills or NIWA laboratories (**Figure B.2**).

The influence of the analytical method change is illustrated by comparing TP results collected from Lake Tarawera. Samples collected by BOPRC from a mid-lake site were compared with samples collected by NIWA from the Tarawera outlet as part of the National River Water Quality Monitoring Network (**NRWQN**). The NIWA samples were consistently analysed over time with the same method, while the BOPRC laboratory analysis changed and did not account for silica interference between 20 August 2010 and September 2019 (inclusive). The BOPRC mid-lake samples between August 2010 and September 2019 had higher results compared to the NIWA outlet site, and BOPRC samples collected outside this period (**Figure B.3**).

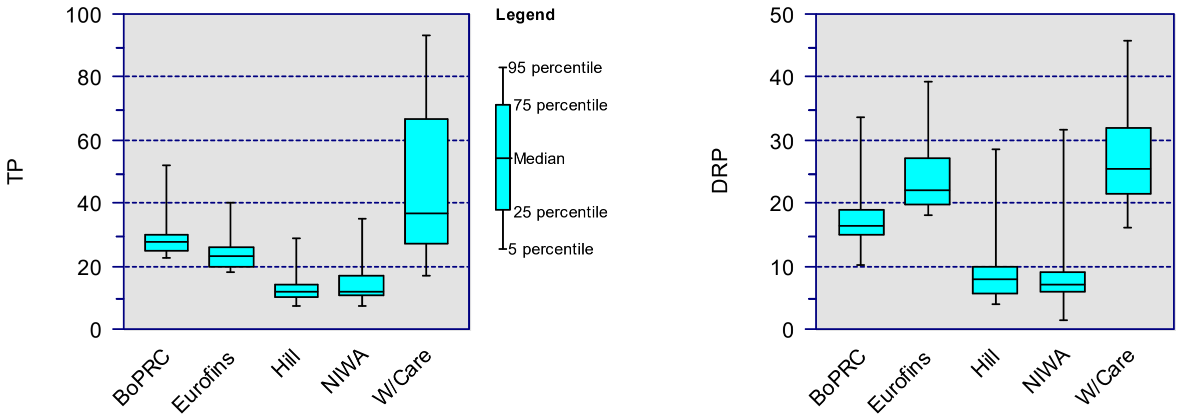


Figure B.2: Results of the inter-laboratory comparison of TP and DRP in Lake Tarawera July 2017 to January 2018 (including all sample depths).

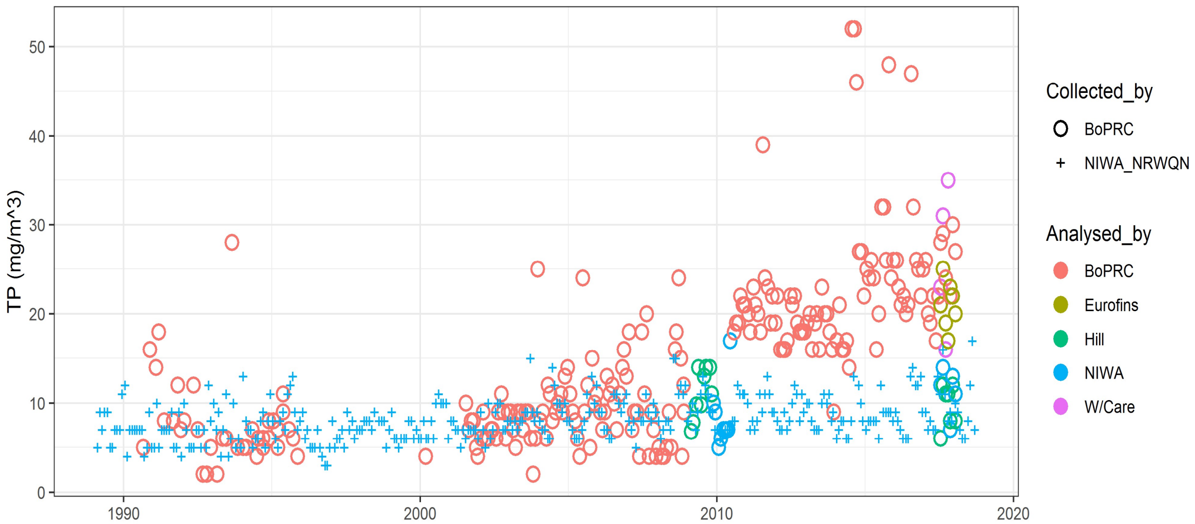


Figure B.3: TP in samples collected at Lake Tarawera outlet by NIWA NRWQN programme and Lake Tarawera mid-lake by BOPRC. Results of the inter-laboratory comparison in 2018 are also shown (from Baisden and McBride 2020).

Interference of analysis by Silica and Arsenic

The reason for the higher TP results with the 2010 BOPRC laboratory analytical method change was identified as primarily additive interference of the phosphorus molybdenum blue method by silica (**Si**) (in the form of silicate), and in some lakes, high concentrations of arsenic (**As**) (in the form of arsenate).

Interference of the P method by Si is more apparent when there are high P to Si concentrations or when silicon is greater than 10 mg/L (Jarvie et al. 2002). This interference can be minimised by adjusting the laboratory technique.

Similarly, the presence of As in the form of arsenate can interfere with analysis of phosphorus, with the arsenate being read as P. This can occur at concentrations above 23 ug/L. This additive interference can be managed by timing of the analysis or eliminated by reduction of As(V) to As(III) by optimisation of the final acidity or using an acidified sodium thiosulfate solution (Jarvie 2000, Linge and Oldham 2001, Worsfold 2016).

The NIWA laboratory method for TP and DRP accounted for silica interference, as did the BOPRC laboratory method used prior to 2010, but the BOPRC laboratory method used between August 2010 and September 2019 (inclusive) did not adjust for either Si or As interference.

The lakes with the highest concentrations of silica and arsenic are Lake Rotomahana, Lake Tarawera, Lake Rotoehu and Ōkataina (**Figure B.4**, **Figure B.5**).

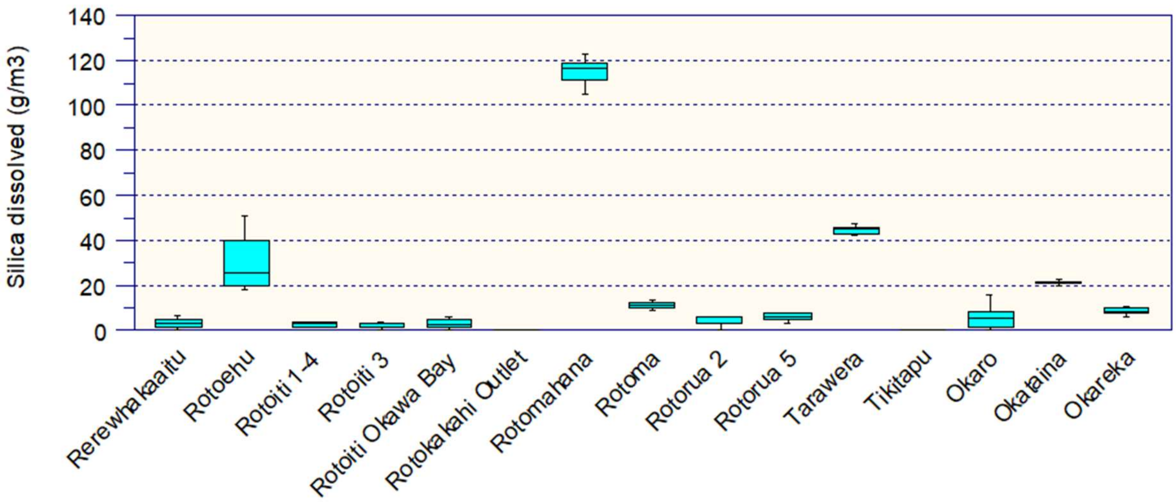


Figure B.4: Dissolved silica in Rotorua lakes. Dataset consisting of annual samples from 2011 to 2020, with periods of monthly sampling in Lakes Rotomahana, Tarawera and Tikitapu.

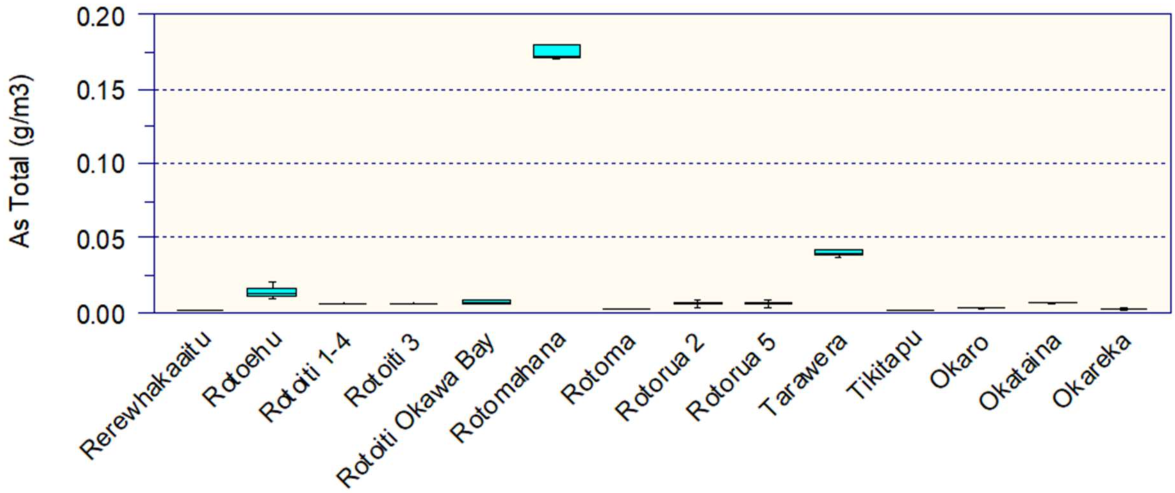


Figure B.5: Total arsenic in Rotorua lakes. Dataset of monthly sampling from 2010 to 2020 for lakes Rotoehu, Rotorua, Ōkaro and Ōkāreka, and occasional intermittent sampling from the other lakes.

Correcting high bias from BOPRC laboratory result

The issue of high bias in the BOPRC laboratory, applied to BOPRC analytical results for the period from August 2010 when the laboratory moved from cadmium column phosphorus analysis (NWASCO Misc Pub. No38, 1982 Acid-persulphate digestion) to flow injection analysis (FIA; Acid persulphate digestion, molybdate colorimetry. FIA. APHA 4500-P H). To address this issue, a new method was trialled by BOPRC laboratory from early October 2018 to June 2019 for all lake sites[4]. The new method, as used in the trial, was formally adopted by BOPRC laboratory in October 2019.

The trial data was used to develop corrections factors for each lake. These correction factors can be used to correct the lake TP data for the period August 2010 to September 2019 (incl.) (**Table B.1**). Data from the period when the Trial was running can be used instead of corrections for the dates where it is available.

Correction functions for TP and DRP were developed for each lake by Troy Baisden from the linear regression of the BOPRC 2010 method (x-axis) and the Trial method (y-axis) (**Figure B.6** and **Figure B.7**). The regressions were forced so as to use a common gradient for each lake but have different offset constants, with the gradient used equivalent to the gradient from a linear regression of all the lake data combined. The exception was Lake Rotomahana where the data was adjusted using a simple offset equal to the median difference between the two methods. The R^2 values of functions derived by this method were the same for each lake (within three decimal places) as the R^2 from a linear regression allowing variable gradients and constants.

[4] The period of time for the trial method was extended for Lake Rotomahana (to include July 2019-August 2019), Lake Tarawera (to include July 2019 and September 2019), and Lake Tikitapu (to include September 2019).

The relationship between the two analytical methods varied strongly between the lakes. In most lakes the corrected data resulted in lower TP, and this tended to be strongest in lakes with high concentrations of Si and As. More specifically, the relative magnitude of correction required was correlated to Si:TP ratio, i.e. a high Si:TP ratio was associated with the ratio of TP (after correction):TP (before correction) being lower, i.e. Rotomahana, Tarawera, Rotomā, Ōkataina and Rotoehu had corrected TP data higher than uncorrected TP data by multiples of 0.46, 0.52, 0.52, 0.47 and 0.68 respectively (**Table B.1, Figure B.8, Figure B.9**).

The correction functions derived for Lake Rerewhakaaitu and Lake Rotoiti made negligible difference to TP concentrations, and correction function for Lake Tikitapu caused an increase rather than a decrease of TP results. It is not clear why the relationship between the 2010 analytical method and the Trial method was the opposite for Lake Tikitapu. Substance that can cause a subtractive interference with the molybdenum blue method include organic acids, fluoride and chloride; also multifunctional (additive or subtractive) interference can occur with sulphide, iron and some surfactants (Nagul et al. 2015).

For most lakes, the function for TP had high R^2 values (i.e. data is tightly clustered around the regression line), but some lakes had poor R^2 values, these were Rotomahana, Rotomā and Ōkataina (**Table B.1)**. The lakes with the lowest R^2 values also had a high Si:TP ratio.

Table B.1: Lake specific functions used to adjust BOPRC laboratory TP results from the period August 2010 to September 2019 (inclusive). Also shown is the median difference in values between the trial and the BOPRC laboratory, count of data used in the analysis and the R^2 value of the regression using the function.

Lake	Function to correct TP for period Aug 10 to Sept 19	Median TP difference (Trial-BOPRC)	count	TP RSQ	TP median	Si:TP
Ōkāreka	y = 0.977 [TPx] - 1.98	-2	30	0.98	7.8	905
Okaro	y = 0.977 [TPx] - 3.78	-4	33	1.00	32.2	88
Okataina	y = 0.977 [TPx] - 6.04	-6	27	0.56	6.0	2437
Rerewhakaaitu	y = 0.977 [TPx] + 0.61	0	21	0.91	9.4	317
Rotoehu	y = 0.977 [TPx] - 9.86	-11	37	0.94	22.4	1120
Rotoiti	y = 0.977 [TPx] + 1.02	0	72	1.00	21.0	70
Rotokakahi	y = 0.977 [TPx] - 2.98	-3.5	10	0.92	13.6	
Rotomā	y = 0.977 [TPx] - 3.21	-3	27	0.18	3.6	2559
Rotomahana	y = [TPx] - 27	-27	33	0.05	22.2	4648
Rotorua	y = 0.977 [TPx] - 1.47	-2	114	0.99	16.5	330
Tarawera	y = 0.977 [TPx] - 9.65	-10	27	0.87	9.9	5025
Tikitapu	y = 0.977 [TPx] + 1.10	1	29	0.73	5.0	70

Dissolved Reactive Phosphorus

Lake	Function to correct DRP for period Aug 10 to Sept 19	Median DRP difference (Trial-BOPRC)	count	DRP RSQ	DRP median
Ōkāreka	y = 0.94 [DRPx] - 1.03	-1	27	0.32	1.5
Okaro	y = 0.94 [DRPx] - 3.95	-4.5	32	0.89	2.0
Okataina	y = 0.94 [DRPx] - 3.33	-3	21	0.84	1.6
Rerewhakaaitu	y = 0.94 [DRPx] - 0.46	0	19	0.03	1.5
Rotoehu	y = 0.94 [DRPx] - 7.6	-10	33	0.85	2.0
Rotoiti	y = 0.94 [DRPx] - 0.76	-2	56	0.97	5.0
Rotokakahi	y = 0.94 [DRPx] - 2.64	-2	9	0.01	1.3
Rotomā	y = 0.94 [DRPx] - 2.04	-2	21	0.05	0.9
Rotomahana	y = [DRPx] - 11	-11	29	0.06	11.0
Rotorua	y = 0.94 [DRPx] - 1.84	-2	112	0.25	0.1
Tarawera	y = 0.94 [DRPx] - 5.97	-8	27	0.83	5.8
Tikitapu	y = 0.94 [DRPx] + 0.38	1	26	0.13	1.4

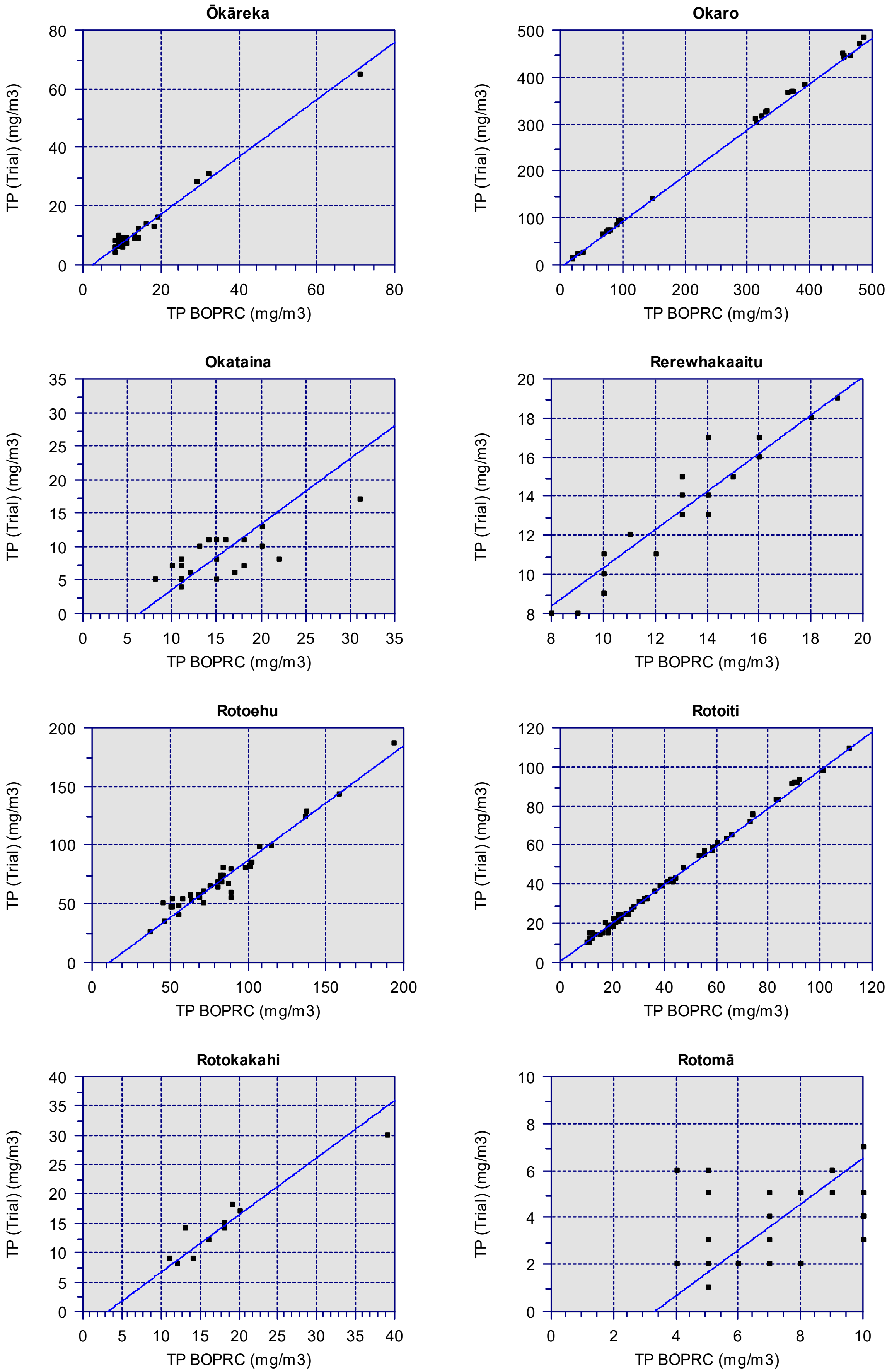


Figure B.6: Total phosphorus as analysed by BOPRC 2010 method and the Trial of the new method, September 2018 to June/September 2019 at all sample depths, and corresponding regressions.

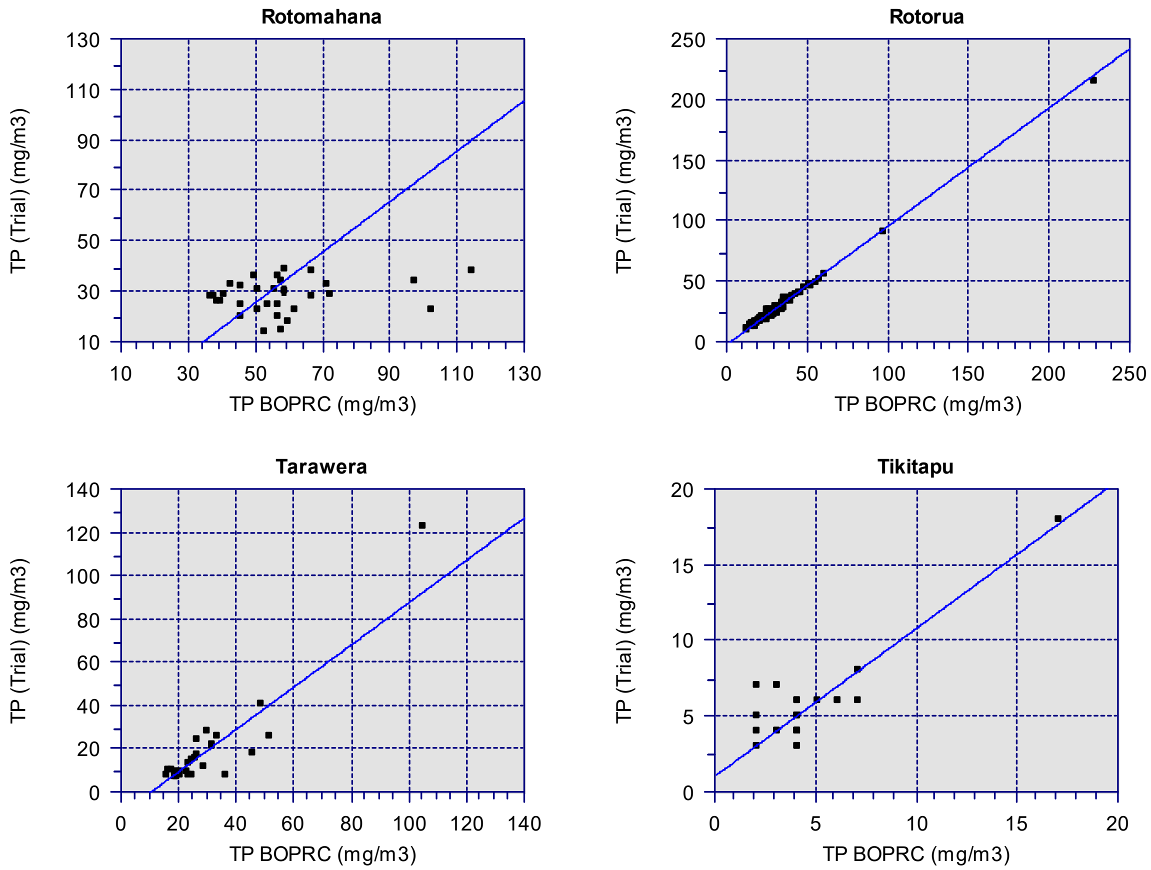


Figure B.6 b: Total phosphorus as analysed by BOPRC 2010 method and the Trial of the new method, September 2018 to June/September 2019 at all sample depths, and corresponding regressions.

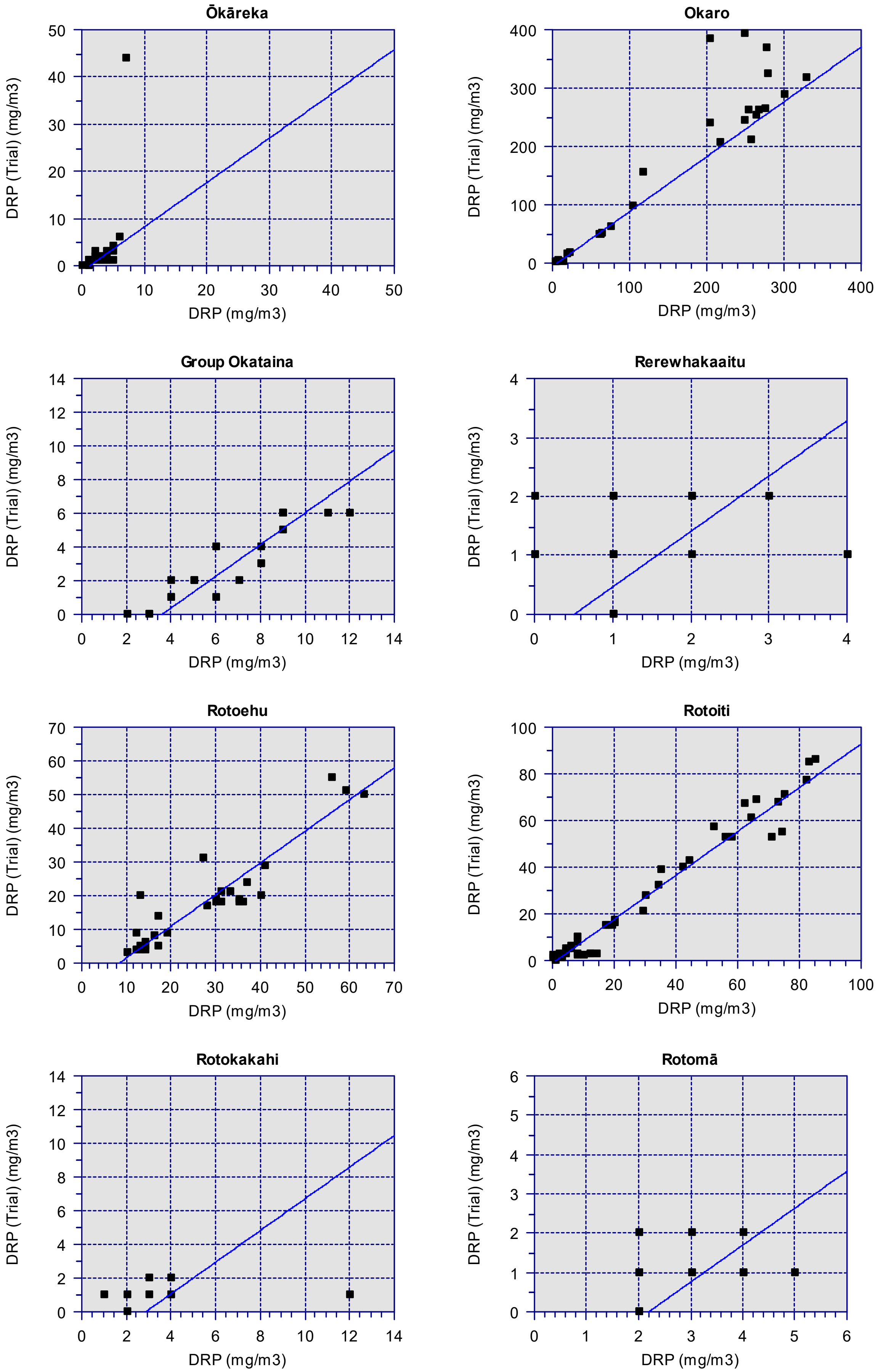


Figure B.7: DRP as analysed by BOPRC 2010 method and the Trial of the new method, September 2018 to June/September 2019 at all sample depths, and corresponding regressions.

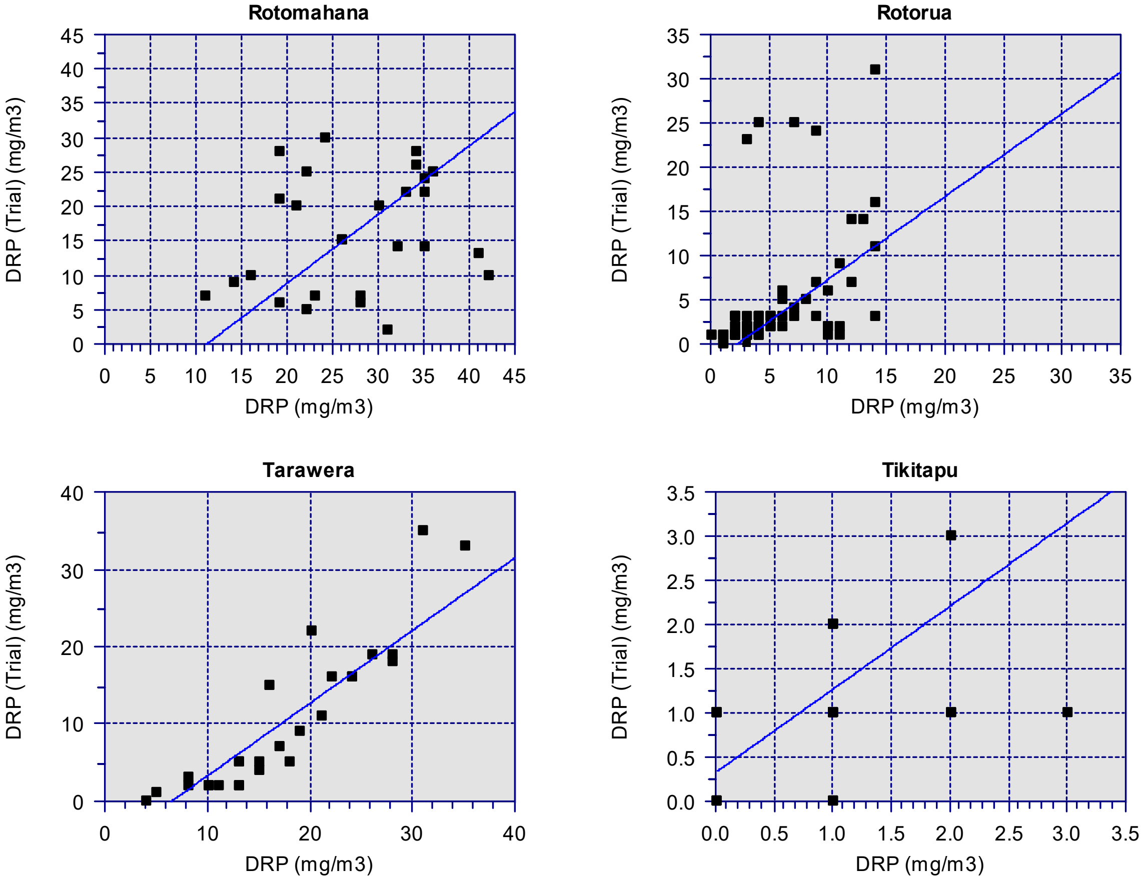


Figure B.7b: Dissolved reactive phosphorus as analysed by BOPRC 2010 method and the Trial of the new method, September 2018 to June/September 2019 at all sample depths, and corresponding regressions.

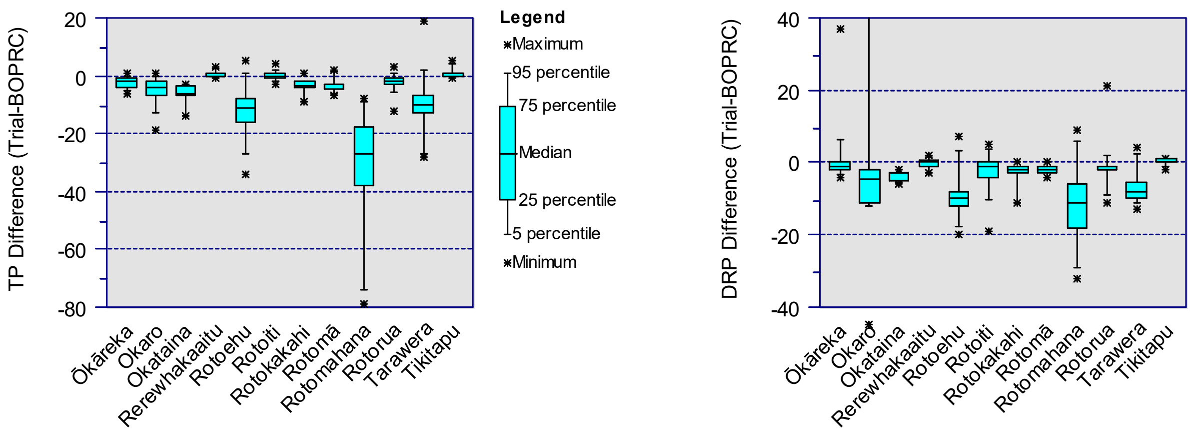


Figure B.8: Difference between the Trial results and BOPRC laboratory 2010 method for total phosphorus and dissolved reactive phosphorus. The DRP graph’s y-axis is truncated.

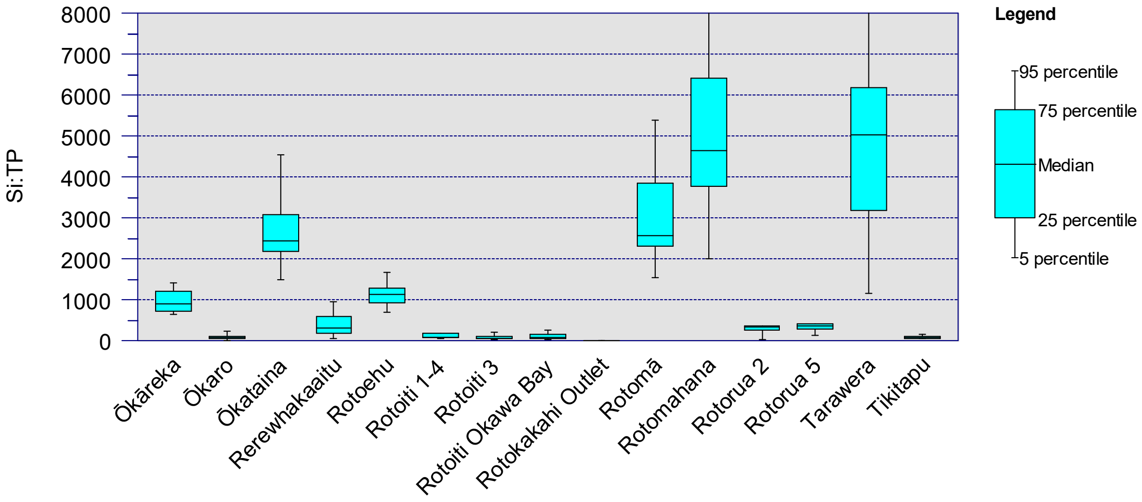


Figure B.9: Ratio of dissolved silica to total phosphorus in each of the Rotorua Lakes

Residual variability in TP results due variability in Si and As

The functions are not perfect, and do not explain all of the variation, in part because there is variation in the concentration of silica and arsenic within the lakes. The lakes have strong interannual and seasonal variations in Si (**Figure B.10** and **Figure B.11**) and As (**Figure B.12**). This variability will still be apparent in the TP and DRP datasets for the period (Oct 2010 to Sept 2019), and it will be most apparent in the lakes with a high ratio of Si:TP (and As:TP) as previously discussed.

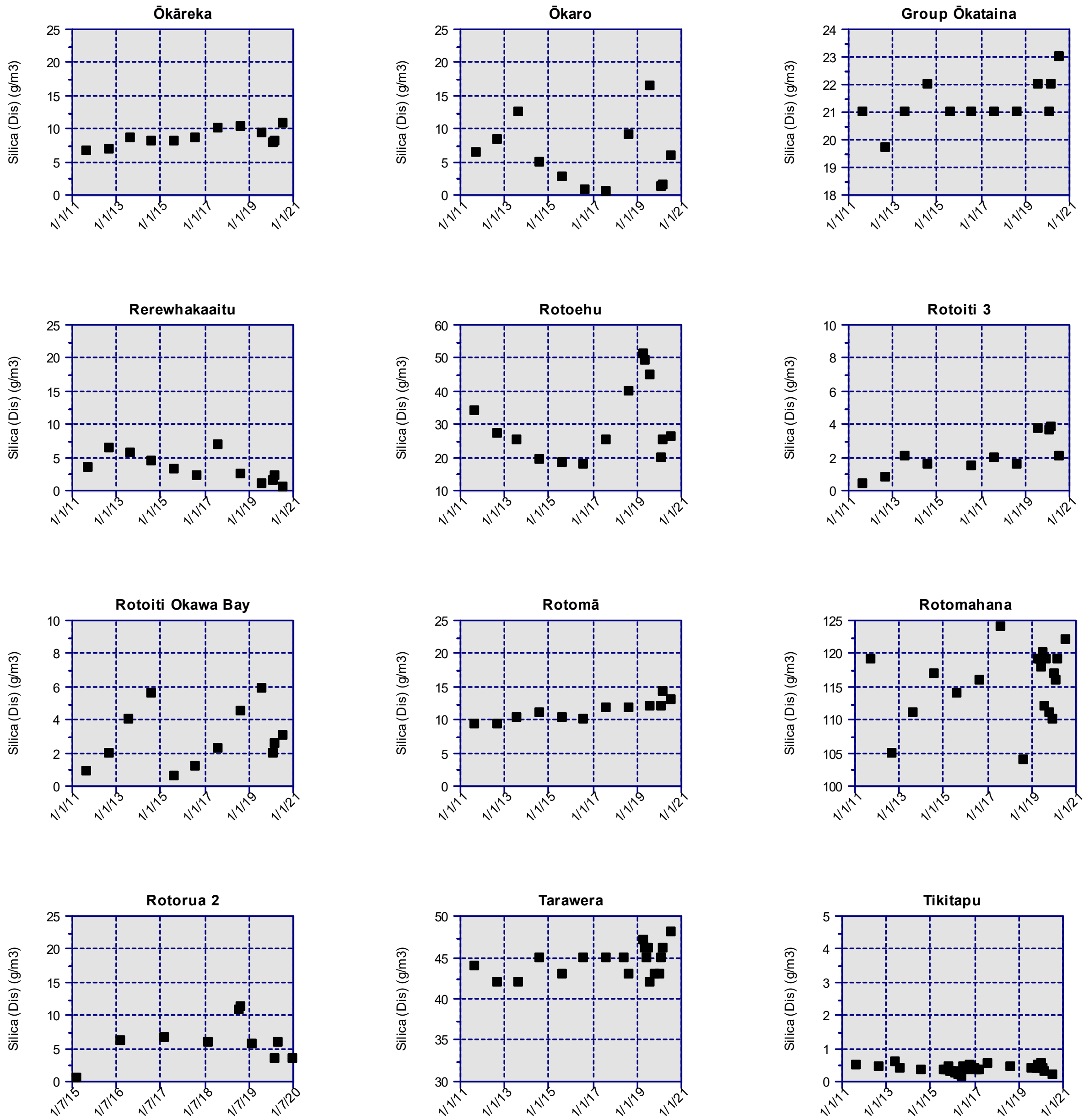


Figure B.10: Variation in total silica concentration in Rotorua Lakes.

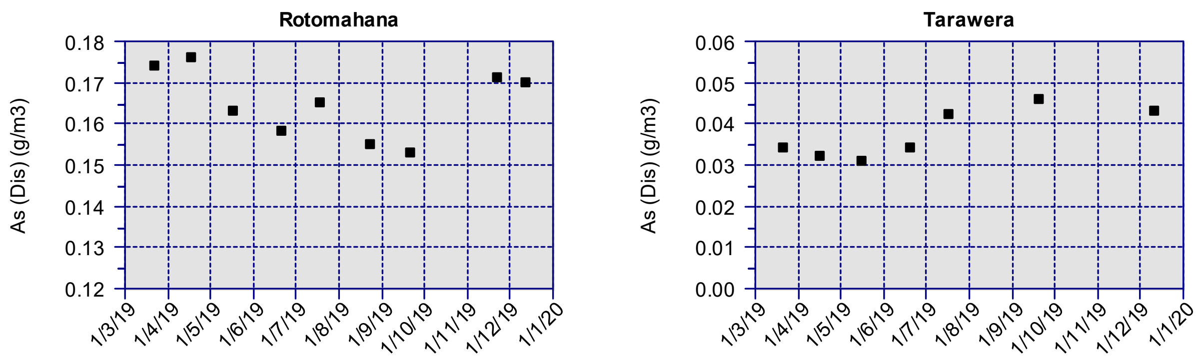


Figure B.11: Dissolved arsenic concentration in Lakes Rotomahana and Tarawera during 2019 (top water)

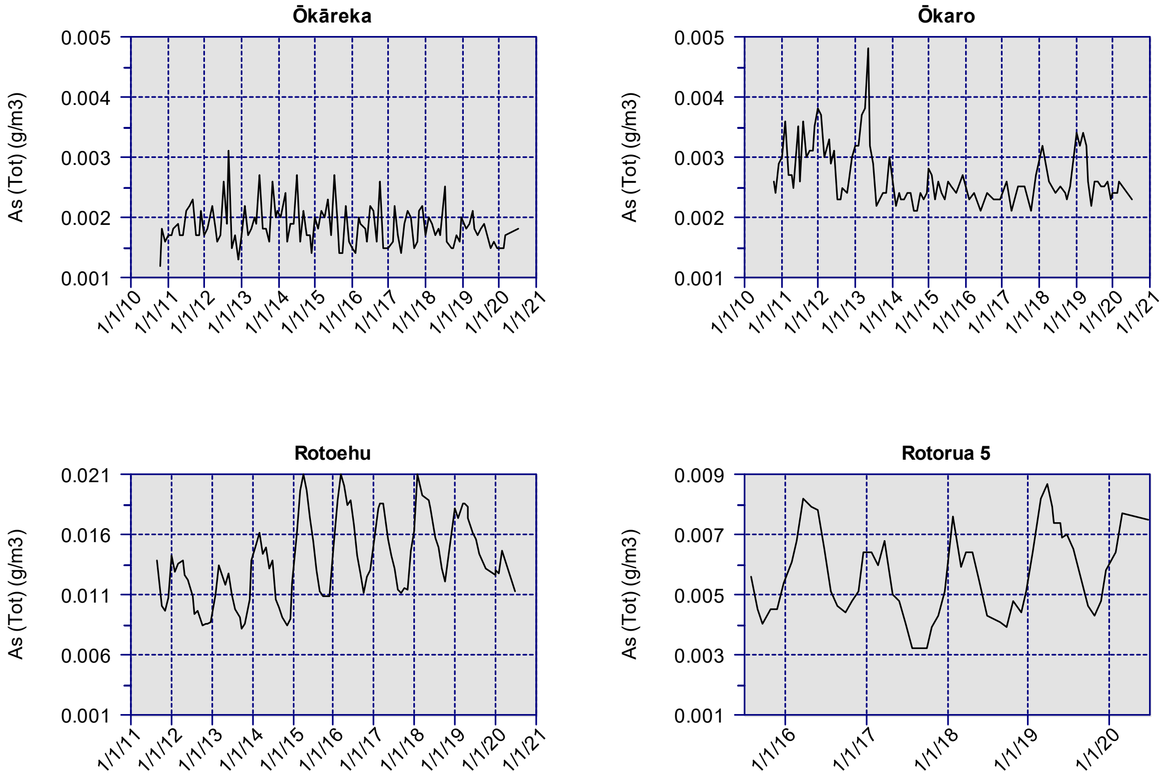


Figure B.12: Total arsenic concentration in Lakes Ōkāreka, Okaro, Rotoehu and Rotorua (top water).

Conclusion

A phosphorus analysis method used by BOPRC laboratory between August 2010 and September 2019 (inclusive) was biased high due to interference by Si and As in most Rotorua Lakes. The trial of a new analytical method has allowed development of lake specific functions to adjust for the analytical bias in P analysis. These adjustments should generally be used when undertaking analysis of water quality state or trends in the Rotorua lakes during the August 2010 to September 2019 period.

Even after applying the functions to P data in the Rotorua lakes, there will still be variability in the P dataset due to seasonal and interannual variability in Si and As concentrations within many lakes. This will be most apparent in the lakes where the high-bias due to the analytical method change was greatest, i.e. Lakes Rotomahana, Tarawera, Rotomā, Ōkataina and Rotoehu.

Total Nitrogen

TN Laboratory change background

In October 2008, the BOPRC laboratory started using Hill Laboratory to analysis TN by a different Total Kjeldahl nitrogen (**TKN**) method; and in November 2009 the BOPRC laboratory changed its method for analysing TN in water samples from calculation of TKN plus nitrite-nitrate nitrogen (**NNN**) (called here **TN-K**), to a direct measurement by alkaline persulphate digestion (called here **TN-A**). The

TN-A method has more precise results and has a lower detection limit [5] than the TN-K method, making it better suited to lake water samples (Davies-Colley et al. 2012, NEMS 2019). However, the TN-A method is known to under-report results (has a low bias) when the concentration of total suspended solids (**TSS**) is high (>20 mg/L) (NEMS 2019).

The influence of the analytical method change is illustrated by comparing total nitrogen results collected from Lake Tarawera; samples collected by BOPRC from a mid-lakes site, have been compared with samples collected by NIWA from the Tarawera outlet as part of the National River Water Quality Monitoring Network (**NRWQN**). Over this time, the NIWA samples were consistently analysed using a TN-A method, while the BOPRC samples were analysed by TN-K prior to November 2009. The BOPRC TN-K samples (before October 2008) had higher results compared to the NIWA outlet site, the Hill Laboratory TN-K method (October 2008-October 2009), and the BOPRC laboratory TN-A method used since November 2009 (**Figure B.13**).

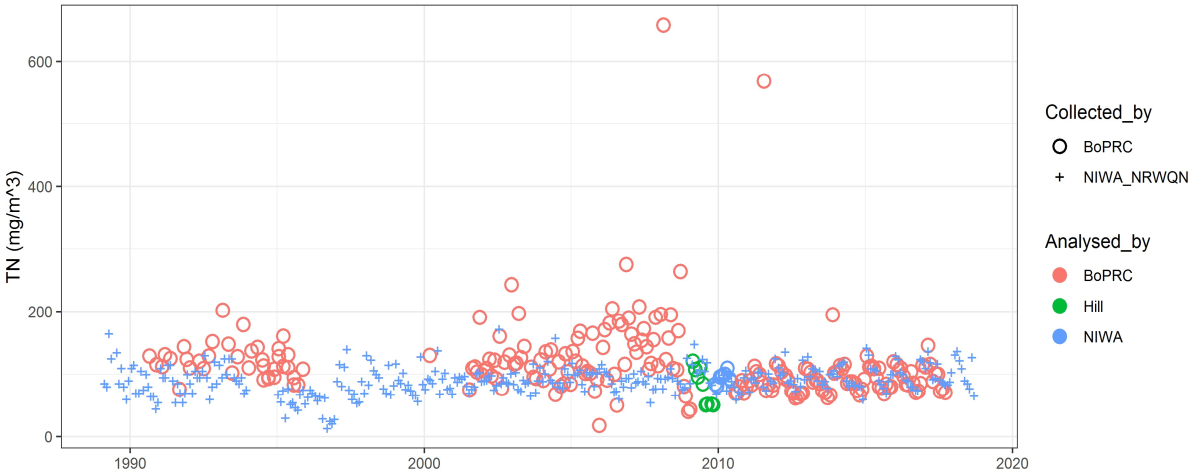


Figure B.13: TN in samples collected at Lake Tarawera outlet by NIWA NRWQN programme and Lake Tarawera mid-lake by BOPRC (from Baisden and McBride 2020). BOPRC samples were analysed as TN-K before November 2009 and as TN-A from this date.

TN Discussion

Rus et al. (2012) found for rivers in the USA that TN-K was less precise and overestimated "true" TN by *ca*. 3.1% (0.04 mg/L), while TN-A was more precise and underestimated "true" TN by *ca*. -3.2% (0.05 mg/L) when TSS was low. The magnitude of under-estimation of TN by TN-A increases with higher concentrations of TSS in the water. Laboratory measurements conducted in nutrient fortified water with no sediment present found TN-A had no detectable bias compared to "true" TN (varied by 0.05 mg/L and average of 0.00 mg/L).

Davies-Colley and McBride (2016) examined the relationship between TN-A and TN-K for rivers in the Wellington region. They found that TN-A concentrations were similar to TN-K at low SPM

[5] The detection limits for TN-A and TN-K are 0.01 mg/L and 0.11 mg/L respectively, but the TN-K detection limit can be reduced to 0.05 mg/L with duplicate testing (NEMS 2019).

concentration, but at higher concentrations (total suspended solids (TSS) > 10 mg/l; visual clarity < 0.6 m), TN-A became systematically lower than TN-K. Even at very low concentrations of TSS (<1 mg/L), where the ratio of TN-A/TN-K approached 1:1, there was considerable scatter in the data; this was attributed to uncertainties in the measurements.

The results of these investigations suggest that for monitoring of water quality in the Rotorua Te Arawa lakes, changing the analytical method from TN-K to TN-A (as occurred in November 2009) provided more consistent and precise results but the TN-A results may be a little lower than TN-K. Step-change decreases in TN occurred in many lakes (i.e. Ōkataina, Rotoiti, Rotomā, Tarawera, Tikitapu) around 2009 that was not associated with changes in other TLI variables

Based on work from Russ et al. (2012) this low-bias compared to TN-K could be between 0% and 7% but is hard to quantify due to high variability. Hamill and Scholes (2016) compared mean TN over four years before and after the laboratory change and found a possible step change in TN of -50 ppb, which would influence lake TLI scores by 0.03 to 0.15 TLI units. However, this work could not fully exclude the influence of other factors causing the change. To better understand the relative bias between TN-K and TN-A for lakes would require a more focused investigation. However, the issue could also be addressed with a pragmatic interpretation of the targets

The water quality data being considered when setting the TLI targets mostly used the TN-K method analysing TN, thus it is possible that the TLI targets are high (i.e. less stringent) compared to TLI determined using current TN-A data. However, this issue does not currently justify a change in the TLI targets because there remains uncertainty about the relative bias between the two methods when applied to the Rotorua lakes. Nevertheless, this issue may justify being more conservative when setting triggers for taking action.

References

Baisden T, McBride C 2020. *P corrections for Lake Tarawera Model & TLI Review WQTAG 19 May 2020*. Presentation to Rotorua Lakes Technical Advisory Group (TAG), Bay of Plenty Regional Council.

Davies-Colley RJ, McBride G 2016. Accounting for changes in method in long-term nutrient data. Recommendations based on analysis of paired SoE data from Wellington rivers. Prepared for the Ministry for the Environment by NIWA. NIWA Client Report No: HAM2016-070

Davies-Colley RJ, Hughes AO, Verburg P, Storey R. 2012. *National Environmental Monitoring and Reporting (NEMaR) Variables Step 2*. Prepared for the Ministry for the Environment by NIWA. NIWA Client Report HAM2021-092

Jarvie HP, Withers PJA, Neal C, 2002. Review of robust measurement of phosphorus in river water: sampling, storage, fractionation and sensitivity. *Hydrology and Earth System Sciences*, 6(1), 113–132

Milne J. R, Perrie A., Robinson P. Davies-Colley R. J. 2014. National consistency in nutrient test methods: assessing the implications of changing methods on long-term water quality datasets – Part 1. Water Symposium, NZ Freshwater Sciences and NZ Hydrological Society joint annual conference, 24-28 November 2014, Blenheim.

Scholes 2020: *Rotorua Lakes 2018-2019 TLI Update*. Memo from Paul Scholes to Helen Creagh, Bay of Plenty Regional Council. 12 August 2020.

Nagul EA, McKelvie ID, Warsfold P, Kolev SD 2015. The molybdenum blue reaction for the determination of orthophosphate revisited: Opening the black box. *Analytica Chimica Acta 890*, 60-82. doi: 10.1016/j.aca.2015.07.030.

Rus, D.L., Patton, C.J., Mueller, D.K. and Crawford, C.G. 2012. Assessing total nitrogen in surface-water samples - precision and bias of analytical and computational methods. US Geological Survey Scientific Investigations Report, 2012-5281: 38.

Worsfold P 2016. *Determination of phosphorus in natural waters: A historical review*. University of Plymouth. https://pearl.plymouth.ac.uk

Appendix C Trophic Level Index formula for TL_{-SD}

Introduction to Trophic Level Index

Lake water quality is often expressed in terms of trophic state, which refers to the production of algae, epiphytes and macrophytes in a lake. The trophic state of each lake was assessed using the Trophic Level Index (**TLI**) (Burns et al. 2000).

The TLI integrates four key measures of lake trophic state - total nitrogen, total phosphorus, chlorophyll-*a* and Secchi depth. 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 indicative of accelerated eutrophication as evidence more nutrients, more algal productivity and reduced water clarity. Trophic state categories and values of key variables defining the boundaries are show in **Table C.1**.

Table C.1*: Definition of Trophic Levels based on water quality measures (source Burns et al. 2000)*

Trophic State	TLI Score	Chl-*a* (mg/m^3)	Secchi depth (m)	TP (mg/m^3)	TN (mg/m^3)
Ultra-microtrophic	<1	< 0.33	> 25	< 1.8	< 34
Microtrophic	1 - 2	0.33 – 0.82	15 - 25	1.8 – 4.1	34 - 73
Oligotrophic	2 - 3	0.82 - 2.0	15 - 7.0	4.1 – 9.0	73 - 157
Mesotrophic	3 - 4	2.0 - 5.0	7.0 - 2.8	9.0 - 20	157 - 337
Eutrophic	4 - 5	5.0 - 12	2.8 - 1.1	20 – 43	337 - 725
Supertrophic	5 - 6	12-31	1.2 - 0.4	43-96	725 - 1558
Hypertrophic	>6	>31	<0.4	>96	>1558

Calculating the TLI

The TLI is traditionally calculated using annual average values of TN, TP, Secchi depth and chlorophyll-*a* from the integrated top water samples (i.e. the epilimnion) (Burns et al. (2000).

For some purposes, (e.g. trend analysis) the TLI is calculated for each individual sample occasions, and then averaged over a year or multi-year period. The two methods produce slightly different results due to how the log function in the equations; the original method calculates a log of average values, the alternative method calculates an average of log values. A comparison of the two approaches found that the method based on individual sample occasions resulted in consistently higher TLI scores than the Burns et al (2000) method (average difference of +. 1.8%). The maximum differences were for Lake Ōkaro (6%) and Lake Rotomā (3.1%) (Hudson et al. 2011; Verberg et al. 2010). Schallenberg and Zon (2021) recommended applying the original method.

In this report, the TLI was calculated using the following regression equations as applied to the Lake Watch software:

$$TL\text{-}n = -3.61+3.01 \log(TN)$$

$$TL\text{-}p = 0.218+2.92 \log(TP)$$

$$TL\text{-}s = 5.56+2.6 \log(1/SD - 1/40)$$

$$TL\text{-}c = 2.22+2.54 \log(Chl\ a)$$

$$TLI = (TL\text{-}n + TL\text{-}p + TL\text{-}s + TL\text{-}c)/4$$

where:

TN = total nitrogen (mg/m^3)

TP = total phosphorus (mg/m^3)

SD = Secchi depth (m)

Chl-*a* = chlorophyll-*a* (mg/m^3)

Different formula for TL-s

Three different formulas have been described in the literature for calculating **TL-s**. These are:

- Formula applied in BOPRC Lake Watch software: $TL_{S} = 5.56 + 2.60 \log(^{1}/_{SD} - ^{1}/_{40})$
- Formula in Burns et al. (2000): $TL_{S} = 5.10 + 2.27 \log(^{1}/_{SD} - ^{1}/_{40})$
- Formula in Burns et al. (2005): $TL_{S} = 5.10 + 2.60 \log(^{1}/_{SD} - ^{1}/_{40})$

In this report we have used the formula that is incorporated into the BOPRC Lake Watch software. This provides consistency with past calculations of TLI by BOPRC. This formula also provides a better fit with TL-c for the Rotorua Lakes dataset, which is consistent with the original approach used in developing the TLI (**Figure C.1**). The TLI was developed by first deriving a formula for chlorophyll-*a* (TL-c), and then deriving formula for the other variables (TN, TP, SD) as the regression model that provided the best fit with TL-c (using annual average measurements of all lake data combined).

The effect on TLI results of using the Lake Water formula for TL-s compared to the Burns et al. (2000) formula was small, causing only a +0.5% to +1.7% difference in TLI scores, with the largest difference in the more eutrophic lakes. The effect on TLI of using the Burns et al. (2005) formula for TL-s was more pronounced, causing a -0.9% to -4.5% difference in TLI scores, with the strongest difference in the more oligotrophic lakes (**Table C.2**).

It was not clear what TL-s formula was used when calculating TLI values during the process of setting the TLI targets. The difference in TLI values caused by the two methods is too subtle and the documentation of the original methods too vague to allow a reliable retrospective analysis, but it is likely to have been the formula from Burns et al. (2000) (John McIntosh pers. comm 2022).

Schallenberg and Zon (2021) argued that the original TLI method should be used to ensure national consistency in reporting results. However, the difference in TLI scores is small (*ca*. 1.3%), and if BOPRC were to change to use the Burns et al. (2000) TL-s formula, then the formula used within the Lake Watch software should also be changed.

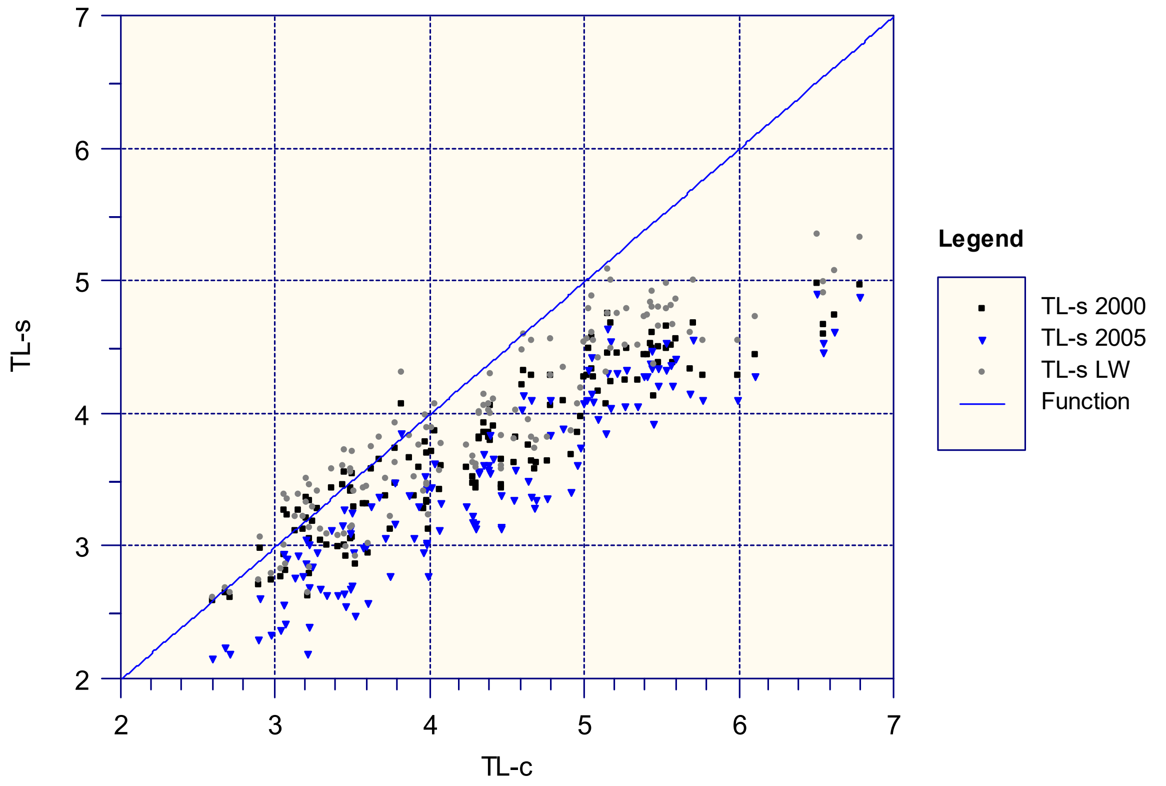


Figure C.1: Comparison of TL-s and TL-c with the different TL-s formulas (Burns et al. 2000, Burns et al. 2005 and Lake Watch (LW)) using data from all Rotorua Lakes 2010-2022.

Table C.2: Effect of using the different formulas for TL-s on the TLI score for each lake (2010-2022)

				TLI (LW) - TLI (2000)		TLI (2005) - TLI (2000)	
Lake	TLI LakeWatch	TLI 2000	TLI 2005	Difference	% Difference	Difference	% Difference
Okareka	3.2	3.1	3.1	0.04	1.1%	-0.08	-2.5%
Okaro	4.9	4.8	4.7	0.07	1.5%	-0.04	-0.9%
Okataina	2.6	2.6	2.5	0.02	0.8%	-0.09	-3.6%
Rerewhakaaitu	3.6	3.5	3.4	0.05	1.3%	-0.07	-2.0%
Rotoehu	4.4	4.3	4.3	0.08	1.8%	-0.04	-0.9%
Rotoiti	3.7	3.6	3.6	0.05	1.2%	-0.07	-1.9%
Rotoiti Okawa Bay	4.4	4.4	4.3	0.07	1.6%	-0.04	-1.0%
Rotoma	2.3	2.3	2.2	0.01	0.5%	-0.10	-4.5%
Rotomahana	3.7	3.7	3.6	0.05	1.4%	-0.06	-1.7%
Rotorua	4.2	4.1	4.1	0.07	1.7%	-0.04	-1.0%
Tarawera	2.8	2.8	2.7	0.03	1.1%	-0.09	-3.1%
Tikitapu	2.9	2.9	2.8	0.04	1.3%	-0.08	-2.7%

Appendix D – Full Trend Analysis results

Seasonal Kendall trend and slope analysis for period January 1991 to December 2021.
Sampling started later for some lakes.

Site	Variable	n	Sampling period	Mean	Median	P	PAC	Slope Likelihood	Trend direction and confidence	Code
Okareka	TL-c	301	1/2/91-1/12/21	3.6	3.6	0.00	-0.35	0.999	Decreasing trend virtually certain	-2
Okareka	TL-s	298	1/2/91-1/12/21	3.0	3.0	0.00	0.28	1.00	Increasing trend virtually certain	2
Okareka	TL-n	291	1/2/91-1/12/21	3.3	3.3	0.00	-0.42	1	Decreasing trend virtually certain	-2
Okareka	TL-p	299	1/2/91-1/12/21	2.7	2.7	0.00	0.72	1.00	Increasing trend virtually certain	2
Okareka	TLI	288	1/2/91-1/12/21	3.2	3.2	0.55	0.04	0.726	Increasing trend about as likely as not	0
Okareka	Chl-a (mg/m3)	301	1/2/91-1/12/21	4.0	3.4	0.00	-1.06	0.999	Decreasing trend virtually certain	-2
Okareka	Clarity (m)	298	1/2/91-1/12/21	7.8	7.7	0.00	-0.59	1	Decreasing trend virtually certain	-2
Okareka	TN (mg/m3)	291	1/2/91-1/12/21	206	199	0.00	-1.10	1	Decreasing trend virtually certain	-2
Okareka	TP (mg/m3)	299	1/2/91-1/12/21	7.7	7.3	0.00	1.43	1.00	Increasing trend virtually certain	2
Okaro	TL-c	265	1/8/91-1/12/21	5.1	5.0	0.00	-0.81	1	Decreasing trend virtually certain	-2
Okaro	TL-s	264	1/8/91-1/12/21	4.5	4.5	0.00	-0.71	1	Decreasing trend virtually certain	-2
Okaro	TL-n	260	1/8/91-1/12/21	5.1	5.1	0.00	-0.59	1	Decreasing trend virtually certain	-2
Okaro	TL-p	263	1/8/91-1/12/21	5.0	5.2	0.00	-1.13	1	Decreasing trend virtually certain	-2
Okaro	TLI	254	1/8/91-1/12/21	4.9	5.0	0.00	-0.80	1	Decreasing trend virtually certain	-2
Okaro	Chl-a (mg/m3)	265	1/8/91-1/12/21	24.7	12.4	0.00	-2.95	1	Decreasing trend virtually certain	-2
Okaro	Clarity (m)	264	1/8/91-1/12/21	2.7	2.4	0.00	2.54	1.00	Increasing trend virtually certain	2
Okaro	TN (mg/m3)	260	1/8/91-1/12/21	864	806	0.00	-2.21	1	Decreasing trend virtually certain	-2
Okaro	TP (mg/m3)	263	1/8/91-1/12/21	60.8	50.0	0.00	-4.38	1	Decreasing trend virtually certain	-2
Okataina	TL-c	265	1/1/91-1/12/21	3.0	3.0	0.00	-0.43	0.999	Decreasing trend virtually certain	-2
Okataina	TL-s	260	1/1/91-1/12/21	2.6	2.6	0.01	-0.24	0.993	Decreasing trend very likely	-2
Okataina	TL-n	256	1/1/91-1/12/21	2.5	2.4	0.00	-1.22	1	Decreasing trend virtually certain	-2
Okataina	TL-p	259	1/1/91-1/12/21	2.6	2.6	0.14	-0.20	0.933	Decreasing trend possible	-1
Okataina	TLI	254	1/1/91-1/12/21	2.7	2.7	0.00	-0.49	1	Decreasing trend virtually certain	-2
Okataina	Chl-a (mg/m3)	265	1/1/91-1/12/21	2.3	2.0	0.00	-1.01	0.999	Decreasing trend virtually certain	-2
Okataina	Clarity (m)	260	1/1/91-1/12/21	10.2	10.3	0.01	0.40	0.99	Increasing trend very likely	2
Okataina	TN (mg/m3)	256	1/1/91-1/12/21	116	101	0.00	-2.33	1	Decreasing trend virtually certain	-2
Okataina	TP (mg/m3)	259	1/1/91-1/12/21	7.5	6.7	0.14	-0.36	0.933	Decreasing trend possible	-1
Rerewhakaaitu	TL-c	279	1/3/91-1/12/21	3.6	3.5	0.03	0.29	0.99	Increasing trend very likely	2
Rerewhakaaitu	TL-s	274	1/8/91-1/12/21	3.5	3.5	0.81	0.02	0.597	Trend unlikely	0
Rerewhakaaitu	TL-n	274	1/3/91-1/12/21	4.1	4.1	0.00	-0.15	1	Decreasing trend virtually certain	-2
Rerewhakaaitu	TL-p	281	1/3/91-1/12/21	2.9	3.0	0.00	0.79	1.00	Increasing trend virtually certain	2
Rerewhakaaitu	TLI	270	1/3/91-1/12/21	3.5	3.5	0.01	0.22	1.00	Increasing trend virtually certain	2
Rerewhakaaitu	Chl-a (mg/m3)	279	1/3/91-1/12/21	4.1	3.3	0.03	0.80	0.99	Increasing trend very likely	2
Rerewhakaaitu	Clarity (m)	274	1/8/91-1/12/21	5.8	5.5	0.81	-0.06	0.599	Trend unlikely	0
Rerewhakaaitu	TN (mg/m3)	274	1/3/91-1/12/21	372	364	0.00	-0.48	1	Decreasing trend virtually certain	-2
Rerewhakaaitu	TP (mg/m3)	281	1/3/91-1/12/21	9.3	9.0	0.00	1.67	1.00	Increasing trend virtually certain	2
Rotoehu	TL-c	276	1/6/95-1/12/21	4.7	4.7	0.20	-0.16	0.9	Decreasing trend possible	-1
Rotoehu	TL-s	244	1/9/99-1/12/21	4.4	4.3	0.61	0.00	0.699	Decreasing trend about as likely as not	0
Rotoehu	TL-n	275	1/6/95-1/12/21	4.1	4.1	0.00	-0.45	1	Decreasing trend virtually certain	-2
Rotoehu	TL-p	277	1/6/95-1/12/21	4.4	4.3	0.03	-0.25	0.985	Decreasing trend very likely	-1
Rotoehu	TLI	274	1/6/95-1/12/21	4.4	4.4	0.00	-0.29	1	Decreasing trend virtually certain	-2
Rotoehu	Chl-a (mg/m3)	276	1/6/95-1/12/21	11.3	9.2	0.20	-0.62	0.9	Decreasing trend possible	-1
Rotoehu	Clarity (m)	244	1/9/99-1/12/21	2.8	2.8	0.61	0.00	0.696	Increasing trend about as likely as not	0
Rotoehu	TN (mg/m3)	275	1/6/95-1/12/21	394	355	0.00	-1.44	1	Decreasing trend virtually certain	-2
Rotoehu	TP (mg/m3)	277	1/6/95-1/12/21	32.3	25.9	0.03	-0.85	0.985	Decreasing trend very likely	-1
Rotoiti	TL-c	300	1/11/91-1/12/21	4.2	4.2	0.01	-0.26	0.997	Decreasing trend virtually certain	-2
Rotoiti	TL-s	304	1/2/91-1/12/21	3.3	3.3	0.53	-0.03	0.738	Decreasing trend about as likely as not	0
Rotoiti	TL-n	305	1/1/91-1/12/21	3.4	3.4	0.00	-0.79	1	Decreasing trend virtually certain	-2
Rotoiti	TL-p	305	1/1/91-1/12/21	4.0	4.0	0.00	0.23	1.00	Increasing trend virtually certain	2
Rotoiti	TLI	299	1/11/91-1/12/21	3.7	3.7	0.00	-0.17	0.999	Decreasing trend virtually certain	-2
Rotoiti	Chl-a (mg/m3)	300	1/11/91-1/12/21	6.8	5.9	0.01	-0.89	0.997	Decreasing trend virtually certain	-2
Rotoiti	Clarity (m)	304	1/2/91-1/12/21	6.1	6.1	0.53	0.07	0.736	Increasing trend about as likely as not	0
Rotoiti	TN (mg/m3)	305	1/1/91-1/12/21	232	214	0.00	-2.05	1	Decreasing trend virtually certain	-2
Rotoiti	TP (mg/m3)	305	1/1/91-1/12/21	22.2	20.5	0.00	0.70	1.00	Increasing trend virtually certain	2

Seasonal Kendall trend and slope analysis for period January 1991 to December 2021

Site	Variable	n	Sampling period	Mean	Median	P	PAC	Slope Likelihood	Trend direction and confidence	Code
Rotokakahi Outlet	TL-c	234	1/11/99-1/12/21	3.7	3.7	0.41	-0.17	0.797	Decreasing trend about as likely as not	-1
Rotokakahi Outlet	TL-s	128	1/8/01-1/12/21	3.9	3.9	0.02	-0.66	0.992	Decreasing trend very likely	-2
Rotokakahi Outlet	TL-n	242	1/7/94-1/12/21	3.5	3.5	0.04	-0.19	0.978	Decreasing trend very likely	-2
Rotokakahi Outlet	TL-p	244	1/7/94-1/12/21	3.5	3.5	0.52	0.08	0.739	Increasing trend about as likely as not	0
Rotokakahi Outlet	TLI	230	1/11/99-1/12/21	3.7	3.6	0.80	-0.04	0.601	Trend unlikely	0
Rotokakahi Outlet	Chl-a (mg/m3)	234	1/11/99-1/12/21	5.5	4.0	0.41	-0.42	0.797	Decreasing trend about as likely as not	-1
Rotokakahi Outlet	Clarity (m)	128	1/8/01-1/12/21	4.1	4.0	0.02	1.97	0.99	Increasing trend very likely	2
Rotokakahi Outlet	TN (mg/m3)	242	1/7/94-1/12/21	244	223	0.04	-0.48	0.978	Decreasing trend very likely	-2
Rotokakahi Outlet	TP (mg/m3)	244	1/7/94-1/12/21	15.5	13.3	0.52	0.23	0.739	Increasing trend about as likely as not	0
Rotoma	TL-c	264	1/1/91-1/12/21	2.4	2.3	0.03	-0.25	0.983	Decreasing trend very likely	-1
Rotoma	TL-s	262	1/1/91-1/12/21	2.3	2.2	0.72	-0.03	0.644	Trend unlikely	0
Rotoma	TL-n	261	1/1/91-1/12/21	2.6	2.6	0.00	-0.75	1	Decreasing trend virtually certain	-2
Rotoma	TL-p	264	1/1/91-1/12/21	1.8	2.0	0.70	0.00	0.652	Trend unlikely	0
Rotoma	TLI	256	1/1/91-1/12/21	2.3	2.3	0.00	-0.31	0.999	Decreasing trend virtually certain	-2
Rotoma	Chl-a (mg/m3)	264	1/1/91-1/12/21	1.3	1.1	0.03	-0.52	0.983	Decreasing trend very likely	-1
Rotoma	Clarity (m)	262	1/1/91-1/12/21	12.7	12.8	0.72	0.05	0.642	Trend unlikely	0
Rotoma	TN (mg/m3)	261	1/1/91-1/12/21	126	112	0.00	-1.58	1	Decreasing trend virtually certain	-2
Rotoma	TP (mg/m3)	264	1/1/91-1/12/21	4.1	4.0	0.70	0.00	0.652	Trend unlikely	0
Rotomahana	TL-c	265	1/3/91-1/12/21	3.7	3.7	0.14	-0.23	0.932	Decreasing trend possible	-1
Rotomahana	TL-s	266	1/3/91-1/12/21	3.7	3.6	0.01	-0.20	0.997	Decreasing trend virtually certain	-2
Rotomahana	TL-n	237	1/5/93-1/12/21	3.3	3.3	0.00	-0.24	0.999	Decreasing trend virtually certain	-2
Rotomahana	TL-p	253	1/3/91-1/12/21	4.3	4.2	0.05	-0.32	0.974	Decreasing trend likely	-1
Rotomahana	TLI	234	1/5/93-1/12/21	3.7	3.7	0.01	-0.23	0.997	Decreasing trend virtually certain	-2
Rotomahana	Chl-a (mg/m3)	265	1/3/91-1/12/21	4.5	3.7	0.14	-0.68	0.932	Decreasing trend possible	-1
Rotomahana	Clarity (m)	266	1/3/91-1/12/21	5.0	4.8	0.01	0.55	1.00	Increasing trend virtually certain	2
Rotomahana	TN (mg/m3)	237	1/5/93-1/12/21	208	200	0.00	-0.64	0.999	Decreasing trend virtually certain	-2
Rotomahana	TP (mg/m3)	253	1/3/91-1/12/21	29.1	24.0	0.05	-1.06	0.974	Decreasing trend likely	-1
Rotorua	TL-c	292	1/12/91-1/12/21	5.0	5.0	0.01	-0.33	0.996	Decreasing trend virtually certain	-2
Rotorua	TL-s	312	1/1/91-1/12/21	4.4	4.4	0.00	-0.17	1	Decreasing trend virtually certain	-2
Rotorua	TL-n	297	1/2/91-1/12/21	4.1	4.1	0.00	-0.44	1	Decreasing trend virtually certain	-2
Rotorua	TL-p	296	1/2/91-1/12/21	4.3	4.3	0.00	-1.14	1	Decreasing trend virtually certain	-2
Rotorua	TLI	285	1/12/91-1/12/21	4.4	4.4	0.00	-0.54	1	Decreasing trend virtually certain	-2
Rotorua	Chl-a (mg/m3)	292	1/12/91-1/12/21	15.2	12.1	0.01	-1.45	0.996	Decreasing trend virtually certain	-2
Rotorua	Clarity (m)	312	1/1/91-1/12/21	2.8	2.7	0.00	0.59	1.00	Increasing trend virtually certain	2
Rotorua	TN (mg/m3)	297	1/2/91-1/12/21	383	353	0.00	-1.31	1	Decreasing trend virtually certain	-2
Rotorua	TP (mg/m3)	296	1/2/91-1/12/21	28.4	25.0	0.00	-3.68	1	Decreasing trend virtually certain	-2
Tarawera	TL-c	264	1/2/91-1/12/21	2.6	2.7	0.08	-0.21	0.961	Decreasing trend likely	-1
Tarawera	TL-s	262	1/2/91-1/12/21	2.9	2.9	0.05	-0.17	0.978	Decreasing trend very likely	-2
Tarawera	TL-n	261	1/2/91-1/12/21	2.4	2.4	0.00	-0.82	1	Decreasing trend virtually certain	-2
Tarawera	TL-p	265	1/2/91-1/12/21	3.0	3.0	0.00	0.73	1.00	Increasing trend virtually certain	2
Tarawera	TLI	257	1/2/91-1/12/21	2.7	2.7	0.53	-0.04	0.74	Decreasing trend about as likely as not	0
Tarawera	Chl-a (mg/m3)	264	1/2/91-1/12/21	1.6	1.5	0.08	-0.49	0.961	Decreasing trend likely	-1
Tarawera	Clarity (m)	262	1/2/91-1/12/21	8.5	8.5	0.05	0.32	0.98	Increasing trend very likely	2
Tarawera	TN (mg/m3)	261	1/2/91-1/12/21	108	102	0.00	-1.51	1	Decreasing trend virtually certain	-2
Tarawera	TP (mg/m3)	265	1/2/91-1/12/21	10.4	9.0	0.00	1.61	1.00	Increasing trend virtually certain	2
Tikitapu	TL-c	266	1/2/91-1/12/21	2.9	2.9	0.51	0.00	0.743	Increasing trend about as likely as not	0
Tikitapu	TL-s	258	1/2/91-1/12/21	3.2	3.2	0.10	-0.16	0.951	Decreasing trend likely	-1
Tikitapu	TL-n	268	1/2/91-1/12/21	3.2	3.2	0.00	-0.36	1	Decreasing trend virtually certain	-2
Tikitapu	TL-p	269	1/2/91-1/12/21	2.2	2.3	0.42	0.00	0.79	Increasing trend about as likely as not	0
Tikitapu	TLI	264	1/2/91-1/12/21	2.9	2.9	0.37	-0.09	0.816	Decreasing trend about as likely as not	-1
Tikitapu	Chl-a (mg/m3)	266	1/2/91-1/12/21	2.1	1.8	0.51	0.00	0.743	Increasing trend about as likely as not	0
Tikitapu	Clarity (m)	258	1/2/91-1/12/21	6.8	6.7	0.10	0.38	0.951	Increasing trend likely	1
Tikitapu	TN (mg/m3)	268	1/2/91-1/12/21	190	181	0.00	-0.89	1	Decreasing trend virtually certain	-2
Tikitapu	TP (mg/m3)	269	1/2/91-1/12/21	5.6	5.0	0.42	0.00	0.79	Increasing trend about as likely as not	0
Rotoiti Okawa Bay	TL-c	234	1/4/01-1/12/21	4.5	4.4	0.08	-0.42	0.96	Decreasing trend likely	-1
Rotoiti Okawa Bay	TL-s	227	1/4/01-1/12/21	4.3	4.3	0.01	-0.34	0.995	Decreasing trend virtually certain	-2
Rotoiti Okawa Bay	TL-n	233	1/6/01-1/12/21	4.0	3.9	0.00	-0.37	0.999	Decreasing trend virtually certain	-2
Rotoiti Okawa Bay	TL-p	236	1/4/01-1/12/21	4.6	4.6	0.04	0.23	0.98	Increasing trend very likely	2
Rotoiti Okawa Bay	TLI	231	1/6/01-1/12/21	4.3	4.3	0.18	-0.18	0.913	Decreasing trend possible	-1
Rotoiti Okawa Bay	Chl-a (mg/m3)	234	1/4/01-1/12/21	12.7	7.4	0.08	-1.44	0.96	Decreasing trend likely	-1
Rotoiti Okawa Bay	Clarity (m)	227	1/4/01-1/12/21	3.1	3.0	0.01	1.13	1.00	Increasing trend virtually certain	2
Rotoiti Okawa Bay	TN (mg/m3)	233	1/6/01-1/12/21	371	307	0.00	-1.11	0.999	Decreasing trend virtually certain	-2
Rotoiti Okawa Bay	TP (mg/m3)	236	1/4/01-1/12/21	36.4	31.3	0.04	0.80	0.98	Increasing trend very likely	2

Seasonal Kendall trend and slope analysis for period January 2001 to December 2021. Samples started July 2001 for Lakes Ōkataina, Rotoiti, Rotokakahi, Tarawera, Tikitapu and Okawa Bay

Site	Variable	n	Mean	Median	P	PAC	Slope Likelihood	Trend direction and confidence	Code
Okareka	TL-c	240	3.5	3.5	0.08	-0.27	0.964	Decreasing trend likely	-1
Okareka	TL-s	238	3.1	3.0	0.05	0.23	0.98	Increasing trend very likely	1
Okareka	TL-n	237	3.3	3.3	0.00	-0.37	1	Decreasing trend virtually certain	-2
Okareka	TL-p	241	2.7	2.8	0.00	0.63	1.00	Increasing trend virtually certain	2
Okareka	TLI	235	3.2	3.2	0.47	0.08	0.764	Increasing trend about as likely as not	0
Okareka	Chl-a (mg/m3)	240	3.7	3.3	0.08	-0.77	0.964	Decreasing trend likely	-1
Okareka	Clarity (m)	238	7.6	7.6	0.05	-0.48	0.977	Decreasing trend very likely	-1
Okareka	TN (mg/m3)	237	198	194	0.00	-0.94	1	Decreasing trend virtually certain	-2
Okareka	TP (mg/m3)	241	7.9	7.8	0.00	1.29	1.00	Increasing trend virtually certain	2
Okaro	TL-c	227	5.0	4.9	0.00	-1.02	1	Decreasing trend virtually certain	-2
Okaro	TL-s	224	4.4	4.4	0.00	-0.88	1	Decreasing trend virtually certain	-2
Okaro	TL-n	222	5.0	5.1	0.00	-0.63	1	Decreasing trend virtually certain	-2
Okaro	TL-p	225	4.9	5.0	0.00	-1.25	1	Decreasing trend virtually certain	-2
Okaro	TLI	219	4.8	4.8	0.00	-0.92	1	Decreasing trend virtually certain	-2
Okaro	Chl-a (mg/m3)	227	23.9	11.7	0.00	-3.42	1	Decreasing trend virtually certain	-2
Okaro	Clarity (m)	224	2.9	2.6	0.00	3.18	1.00	Increasing trend virtually certain	2
Okaro	TN (mg/m3)	222	820	766	0.00	-2.31	1	Decreasing trend virtually certain	-2
Okaro	TP (mg/m3)	225	54.0	42.1	0.00	-4.36	1	Decreasing trend virtually certain	-2
Okataina	TL-c	232	3.0	3.0	0.00	-0.82	1	Decreasing trend virtually certain	-2
Okataina	TL-s	229	2.6	2.6	0.02	-0.33	0.992	Decreasing trend very likely	-2
Okataina	TL-n	228	2.5	2.4	0.00	-1.35	1	Decreasing trend virtually certain	-2
Okataina	TL-p	230	2.6	2.6	0.16	-0.22	0.922	Decreasing trend possible	-1
Okataina	TLI	227	2.7	2.7	0.00	-0.64	1	Decreasing trend virtually certain	-2
Okataina	Chl-a (mg/m3)	232	2.3	2.0	0.00	-2.05	1	Decreasing trend virtually certain	-2
Okataina	Clarity (m)	229	10.2	10.3	0.02	0.54	0.99	Increasing trend very likely	2
Okataina	TN (mg/m3)	228	111	98	0.00	-2.52	1	Decreasing trend virtually certain	-2
Okataina	TP (mg/m3)	230	7.3	6.7	0.16	-0.39	0.922	Decreasing trend possible	-1
Rerewhakaaitu	TL-c	239	3.6	3.5	0.01	0.43	1.00	Increasing trend virtually certain	2
Rerewhakaaitu	TL-s	236	3.4	3.5	0.92	-0.01	0.549	Trend extremely unlikely	0
Rerewhakaaitu	TL-n	233	4.1	4.1	0.01	-0.16	0.998	Decreasing trend virtually certain	-2
Rerewhakaaitu	TL-p	240	3.0	3.1	0.00	0.68	1.00	Increasing trend virtually certain	2
Rerewhakaaitu	TLI	230	3.5	3.5	0.03	0.25	0.98	Increasing trend very likely	2
Rerewhakaaitu	Chl-a (mg/m3)	239	3.9	3.3	0.01	1.35	1.00	Increasing trend virtually certain	2
Rerewhakaaitu	Clarity (m)	236	5.8	5.5	0.92	0.03	0.542	Trend extremely unlikely	0
Rerewhakaaitu	TN (mg/m3)	233	368	360	0.01	-0.50	0.998	Decreasing trend virtually certain	-2
Rerewhakaaitu	TP (mg/m3)	240	9.7	9.4	0.00	1.52	1.00	Increasing trend virtually certain	2
Rotoehu	TL-c	243	4.6	4.6	0.77	-0.05	0.623	Trend unlikely	0
Rotoehu	TL-s	237	4.4	4.3	0.94	0.00	0.53	Trend extremely unlikely	0
Rotoehu	TL-n	242	4.1	4.0	0.01	-0.35	0.997	Decreasing trend virtually certain	-2
Rotoehu	TL-p	244	4.4	4.3	0.09	-0.27	0.956	Decreasing trend likely	-1
Rotoehu	TLI	241	4.4	4.4	0.03	-0.23	0.988	Decreasing trend very likely	-2
Rotoehu	Chl-a (mg/m3)	243	11.1	9.0	0.77	-0.25	0.623	Trend unlikely	0
Rotoehu	Clarity (m)	237	2.9	2.8	0.94	0.00	0.538	Trend extremely unlikely	0
Rotoehu	TN (mg/m3)	242	383	342	0.01	-1.08	0.997	Decreasing trend virtually certain	-2
Rotoehu	TP (mg/m3)	244	32.1	25.0	0.09	-0.88	0.956	Decreasing trend likely	-1
Rotoiti	TL-c	239	4.2	4.2	0.00	-0.79	1	Decreasing trend virtually certain	-2
Rotoiti	TL-s	239	3.3	3.3	0.72	-0.04	0.647	Trend unlikely	0
Rotoiti	TL-n	239	3.4	3.3	0.00	-1.18	1	Decreasing trend virtually certain	-2
Rotoiti	TL-p	239	4.1	4.1	0.56	0.05	0.72	Increasing trend about as likely as not	0
Rotoiti	TLI	239	3.8	3.7	0.00	-0.48	1	Decreasing trend virtually certain	-2
Rotoiti	Chl-a (mg/m3)	239	7.0	6.1	0.00	-2.48	1	Decreasing trend virtually certain	-2
Rotoiti	Clarity (m)	239	6.1	6.0	0.72	0.10	0.64	Trend unlikely	0
Rotoiti	TN (mg/m3)	239	223	192	0.00	-3.02	1	Decreasing trend virtually certain	-2
Rotoiti	TP (mg/m3)	239	23.3	22.0	0.56	0.18	0.72	Increasing trend about as likely as not	0

Seasonal Kendall trend and slope analysis for period January 2001 to December 2021. Samples started July 2001 for Lakes Ōkataina, Rotoiti, Rotokakahi, Tarawera, Tikitapu and Okawa Bay

Site	Variable	n	Mean	Median	P	PAC	Slope Likelihood	Trend direction and confidence	Code
Rotokakahi Outlet	TL-c	228	3.7	3.7	0.36	-0.22	0.827	Decreasing trend about as likely as not	0
Rotokakahi Outlet	TL-s	128	3.9	3.9	0.00	-0.83	0.999	Decreasing trend virtually certain	-2
Rotokakahi Outlet	TL-n	230	3.5	3.5	0.02	-0.26	0.99	Decreasing trend very likely	-2
Rotokakahi Outlet	TL-p	231	3.6	3.5	0.75	0.00	0.632	Trend unlikely	0
Rotokakahi Outlet	TLI	224	3.7	3.6	0.45	-0.09	0.782	Decreasing trend about as likely as not	0
Rotokakahi Outlet	Chl-a (mg/m3)	228	5.4	4.0	0.36	-0.58	0.827	Decreasing trend about as likely as not	0
Rotokakahi Outlet	Clarity (m)	128	4.1	4.0	0.00	2.28	1.00	Increasing trend virtually certain	2
Rotokakahi Outlet	TN (mg/m3)	230	241	222	0.02	-0.70	0.99	Decreasing trend very likely	-2
Rotokakahi Outlet	TP (mg/m3)	231	15.7	13.6	0.75	0.00	0.632	Trend unlikely	0
Rotoma	TL-c	230	2.4	2.3	0.02	-0.33	0.993	Decreasing trend very likely	-2
Rotoma	TL-s	228	2.3	2.2	0.42	0.13	0.79	Increasing trend about as likely as not	1
Rotoma	TL-n	229	2.6	2.5	0.00	-0.82	1	Decreasing trend virtually certain	-2
Rotoma	TL-p	231	1.8	2.0	0.72	0.00	0.647	Trend unlikely	0
Rotoma	TLI	225	2.3	2.3	0.02	-0.33	0.989	Decreasing trend very likely	-2
Rotoma	Chl-a (mg/m3)	230	1.3	1.1	0.02	-0.65	0.993	Decreasing trend very likely	-2
Rotoma	Clarity (m)	228	12.8	13.0	0.42	-0.16	0.796	Decreasing trend about as likely as not	-1
Rotoma	TN (mg/m3)	229	123	111	0.00	-1.70	1	Decreasing trend virtually certain	-2
Rotoma	TP (mg/m3)	231	4.1	4.0	0.72	0.00	0.647	Trend unlikely	0
Rotomahana	TL-c	226	3.7	3.7	0.12	-0.27	0.941	Decreasing trend possible	-1
Rotomahana	TL-s	228	3.6	3.6	0.05	-0.20	0.978	Decreasing trend very likely	-1
Rotomahana	TL-n	224	3.3	3.3	0.01	-0.22	0.994	Decreasing trend very likely	-2
Rotomahana	TL-p	227	4.3	4.2	0.27	-0.23	0.87	Decreasing trend possible	-1
Rotomahana	TLI	221	3.7	3.7	0.01	-0.28	0.998	Decreasing trend virtually certain	-2
Rotomahana	Chl-a (mg/m3)	226	4.4	3.7	0.12	-0.90	0.941	Decreasing trend possible	-1
Rotomahana	Clarity (m)	228	5.1	5.0	0.05	0.53	0.98	Increasing trend very likely	1
Rotomahana	TN (mg/m3)	224	206	199	0.01	-0.53	0.994	Decreasing trend very likely	-2
Rotomahana	TP (mg/m3)	227	28.5	23.7	0.27	-0.76	0.87	Decreasing trend possible	-1
Rotorua	TL-c	240	5.1	5.1	0.00	-1.17	1	Decreasing trend virtually certain	-2
Rotorua	TL-s	239	4.4	4.4	0.00	-0.48	1	Decreasing trend virtually certain	-2
Rotorua	TL-n	241	4.1	4.0	0.00	-0.65	1	Decreasing trend virtually certain	-2
Rotorua	TL-p	241	4.2	4.1	0.00	-1.57	1	Decreasing trend virtually certain	-2
Rotorua	TLI	240	4.4	4.4	0.00	-0.98	1	Decreasing trend virtually certain	-2
Rotorua	Chl-a (mg/m3)	240	16.2	13.5	0.00	-5.19	1	Decreasing trend virtually certain	-2
Rotorua	Clarity (m)	239	2.8	2.7	0.00	1.61	1.00	Increasing trend virtually certain	2
Rotorua	TN (mg/m3)	241	374	341	0.00	-2.07	1	Decreasing trend virtually certain	-2
Rotorua	TP (mg/m3)	241	26.4	21.5	0.00	-5.68	1	Decreasing trend virtually certain	-2
Tarawera	TL-c	233	2.6	2.7	0.78	0.00	0.62	Trend unlikely	0
Tarawera	TL-s	230	2.9	2.9	0.18	-0.15	0.915	Decreasing trend possible	-1
Tarawera	TL-n	230	2.4	2.4	0.00	-0.86	1	Decreasing trend virtually certain	-2
Tarawera	TL-p	233	3.1	3.0	0.00	0.59	1.00	Increasing trend virtually certain	2
Tarawera	TLI	228	2.7	2.7	0.12	-0.13	0.943	Decreasing trend possible	-1
Tarawera	Chl-a (mg/m3)	233	1.6	1.5	0.78	0.00	0.62	Trend unlikely	0
Tarawera	Clarity (m)	230	8.5	8.5	0.18	0.31	0.911	Increasing trend possible	1
Tarawera	TN (mg/m3)	230	105	98	0.00	-1.53	1	Decreasing trend virtually certain	-2
Tarawera	TP (mg/m3)	233	10.8	9.0	0.00	1.39	1.00	Increasing trend virtually certain	2
Tikitapu	TL-c	231	2.9	2.9	0.69	0.00	0.654	Trend unlikely	0
Tikitapu	TL-s	223	3.3	3.2	0.00	-0.54	1	Decreasing trend virtually certain	-2
Tikitapu	TL-n	232	3.2	3.2	0.00	-0.45	1	Decreasing trend virtually certain	-2
Tikitapu	TL-p	233	2.2	2.3	0.97	0.00	0.52	Trend exceptionally unlikely	0
Tikitapu	TLI	230	2.9	2.9	0.05	-0.21	0.975	Decreasing trend likely	-1
Tikitapu	Chl-a (mg/m3)	231	2.1	1.8	0.69	0.00	0.654	Trend unlikely	0
Tikitapu	Clarity (m)	223	6.7	6.5	0.00	1.26	1.00	Increasing trend virtually certain	2
Tikitapu	TN (mg/m3)	232	188	177	0.00	-1.13	1	Decreasing trend virtually certain	-2
Tikitapu	TP (mg/m3)	233	5.5	5.0	0.97	0.00	0.523	Trend exceptionally unlikely	0
Rotoiti Okawa Bay	TL-c	234	4.5	4.4	0.11	-0.43	0.949	Decreasing trend possible	-1
Rotoiti Okawa Bay	TL-s	227	4.3	4.3	0.01	-0.33	0.994	Decreasing trend very likely	-2
Rotoiti Okawa Bay	TL-n	233	4.0	3.9	0.01	-0.33	0.997	Decreasing trend virtually certain	-2
Rotoiti Okawa Bay	TL-p	236	4.6	4.6	0.05	0.23	0.98	Increasing trend very likely	2
Rotoiti Okawa Bay	TLI	231	4.3	4.3	0.26	-0.18	0.874	Decreasing trend possible	-1
Rotoiti Okawa Bay	Chl-a (mg/m3)	234	12.7	7.4	0.11	-1.66	0.949	Decreasing trend possible	-1
Rotoiti Okawa Bay	Clarity (m)	227	3.1	3.0	0.01	1.08	0.99	Increasing trend very likely	2
Rotoiti Okawa Bay	TN (mg/m3)	233	371	307	0.01	-0.92	0.997	Decreasing trend virtually certain	-2
Rotoiti Okawa Bay	TP (mg/m3)	236	36.4	31.3	0.05	0.78	0.98	Increasing trend very likely	2

Seasonal Kendall trend and slope analysis for period January 2010 to December 2021

Site	Variable	n	Mean	Median	P	PAC	Slope Likelihood	Trend direction and confidence	Code
Okareka	TL-c	137	3.5	3.5	0.45	-0.33	0.79	Decreasing trend about as likely as not	0
Okareka	TL-s	136	3.1	3.1	0.51	0.15	0.746	Increasing trend about as likely as not	0
Okareka	TL-n	135	3.2	3.2	0.78	-0.06	0.627	Trend unlikely	0
Okareka	TL-p	138	2.8	2.8	0.00	0.89	1.00	Increasing trend virtually certain	2
Okareka	TLI	134	3.2	3.2	1.00	-0.01	0.515	Trend exceptionally unlikely	0
Okareka	Chl-a (mg/m3)	137	3.6	3.1	0.45	-0.81	0.79	Decreasing trend about as likely as not	0
Okareka	Clarity (m)	136	7.5	7.5	0.51	-0.38	0.76	Decreasing trend about as likely as not	0
Okareka	TN (mg/m3)	135	189	184	0.78	-0.15	0.627	Trend unlikely	0
Okareka	TP (mg/m3)	138	8.2	7.8	0.00	1.87	1.00	Increasing trend virtually certain	2
Okaro	TL-c	139	4.8	4.7	0.24	-0.61	0.888	Decreasing trend possible	-1
Okaro	TL-s	138	4.3	4.2	0.00	-1.19	0.999	Decreasing trend virtually certain	-2
Okaro	TL-n	138	4.9	4.9	0.00	-0.66	1	Decreasing trend virtually certain	-2
Okaro	TL-p	138	4.6	4.6	0.28	-0.30	0.868	Decreasing trend possible	-1
Okaro	TLI	138	4.7	4.6	0.07	-0.55	0.97	Decreasing trend likely	-1
Okaro	Chl-a (mg/m3)	139	20.7	9.3	0.24	-2.00	0.887	Decreasing trend possible	-1
Okaro	Clarity (m)	138	3.2	3.0	0.00	3.69	1.00	Increasing trend virtually certain	2
Okaro	TN (mg/m3)	138	749	683	0.00	-2.05	1	Decreasing trend virtually certain	-2
Okaro	TP (mg/m3)	138	43.5	31.4	0.28	-0.74	0.868	Decreasing trend possible	-1
Okataina	TL-c	132	2.9	2.9	0.04	-0.86	0.984	Decreasing trend very likely	-2
Okataina	TL-s	130	2.6	2.6	0.14	-0.31	0.936	Decreasing trend possible	-1
Okataina	TL-n	132	2.3	2.3	0.02	-0.44	0.99	Decreasing trend very likely	-2
Okataina	TL-p	132	2.5	2.5	0.23	0.41	0.88	Increasing trend possible	1
Okataina	TLI	132	2.6	2.6	0.48	-0.14	0.779	Decreasing trend about as likely as not	0
Okataina	Chl-a (mg/m3)	132	2.1	1.9	0.04	-1.91	0.984	Decreasing trend very likely	-2
Okataina	Clarity (m)	130	10.3	10.5	0.14	0.52	0.931	Increasing trend possible	1
Okataina	TN (mg/m3)	132	92	89	0.02	-0.77	0.99	Decreasing trend very likely	-2
Okataina	TP (mg/m3)	132	6.6	6.0	0.23	0.72	0.88	Increasing trend possible	1
Rerewhakaaitu	TL-c	139	3.6	3.6	0.39	-0.31	0.815	Decreasing trend about as likely as not	0
Rerewhakaaitu	TL-s	139	3.5	3.4	0.00	-0.78	0.999	Decreasing trend virtually certain	-2
Rerewhakaaitu	TL-n	139	4.1	4.1	0.02	-0.34	0.993	Decreasing trend very likely	-2
Rerewhakaaitu	TL-p	139	3.2	3.1	0.00	-0.90	0.999	Decreasing trend virtually certain	-2
Rerewhakaaitu	TLI	139	3.6	3.6	0.01	-0.70	0.996	Decreasing trend virtually certain	-2
Rerewhakaaitu	Chl-a (mg/m3)	139	4.2	3.5	0.39	-1.07	0.815	Decreasing trend about as likely as not	0
Rerewhakaaitu	Clarity (m)	139	5.7	5.7	0.00	1.86	1.00	Increasing trend virtually certain	2
Rerewhakaaitu	TN (mg/m3)	139	356	352	0.02	-1.02	0.993	Decreasing trend very likely	-2
Rerewhakaaitu	TP (mg/m3)	139	10.5	9.6	0.00	-2.14	0.999	Decreasing trend virtually certain	-2
Rotoehu	TL-c	138	4.6	4.6	0.00	1.61	1.00	Increasing trend virtually certain	2
Rotoehu	TL-s	135	4.3	4.3	0.00	1.09	1.00	Increasing trend virtually certain	2
Rotoehu	TL-n	137	4.0	3.9	0.00	1.58	1.00	Increasing trend virtually certain	2
Rotoehu	TL-p	138	4.2	4.2	0.00	1.56	1.00	Increasing trend virtually certain	2
Rotoehu	TLI	137	4.3	4.2	0.00	1.36	1.00	Increasing trend virtually certain	2
Rotoehu	Chl-a (mg/m3)	138	11.1	8.7	0.00	5.53	1.00	Increasing trend virtually certain	2
Rotoehu	Clarity (m)	135	2.9	2.8	0.00	-3.87	1	Decreasing trend virtually certain	-2
Rotoehu	TN (mg/m3)	137	361	307	0.00	4.36	1.00	Increasing trend virtually certain	2
Rotoehu	TP (mg/m3)	138	29.0	22.4	0.00	4.40	1.00	Increasing trend virtually certain	2
Rotoiti	TL-c	139	4.0	4.0	0.95	0.00	0.525	Trend exceptionally unlikely	0
Rotoiti	TL-s	139	3.3	3.3	0.00	0.50	1.00	Increasing trend virtually certain	2
Rotoiti	TL-n	139	3.1	3.1	0.77	0.05	0.615	Trend unlikely	0
Rotoiti	TL-p	139	4.1	4.1	0.01	0.36	1.00	Increasing trend very likely	2
Rotoiti	TLI	139	3.6	3.6	0.07	0.29	0.964	Increasing trend likely	1
Rotoiti	Chl-a (mg/m3)	139	5.8	5.2	0.95	0.00	0.525	Trend exceptionally unlikely	0
Rotoiti	Clarity (m)	139	6.2	6.0	0.00	-1.25	0.998	Decreasing trend virtually certain	-2
Rotoiti	TN (mg/m3)	139	176	175	0.77	0.12	0.615	Trend unlikely	0
Rotoiti	TP (mg/m3)	139	22.3	21.1	0.01	1.16	1.00	Increasing trend very likely	2

Seasonal Kendall trend and slope analysis for period January 2010 to December 2021

Site	Variable	n	Mean	Median	P	PAC	Slope Likelihood	Trend direction and confidence	Code
Rotokakahi Outlet	TL-c	138	3.7	3.7	0.01	-1.02	0.994	Decreasing trend very likely	-2
Rotokakahi Outlet	TL-s	107	3.9	3.9	0.00	-1.06	1	Decreasing trend virtually certain	-2
Rotokakahi Outlet	TL-n	138	3.5	3.4	0.01	-0.41	0.996	Decreasing trend virtually certain	-2
Rotokakahi Outlet	TL-p	138	3.6	3.5	0.00	-1.11	1	Decreasing trend virtually certain	-2
Rotokakahi Outlet	TLI	138	3.6	3.6	0.00	-0.83	1	Decreasing trend virtually certain	-2
Rotokakahi Outlet	Chl-a (mg/m3)	138	4.7	3.9	0.01	-2.60	0.994	Decreasing trend very likely	-2
Rotokakahi Outlet	Clarity (m)	107	4.1	4.0	0.00	3.13	1.00	Increasing trend virtually certain	2
Rotokakahi Outlet	TN (mg/m3)	138	229	216	0.01	-1.02	0.996	Decreasing trend virtually certain	-2
Rotokakahi Outlet	TP (mg/m3)	138	14.8	13.6	0.00	-2.98	1	Decreasing trend virtually certain	-2
Rotoma	TL-c	138	2.3	2.3	0.11	0.31	0.95	Increasing trend possible	1
Rotoma	TL-s	136	2.3	2.2	0.00	1.34	1.00	Increasing trend virtually certain	2
Rotoma	TL-n	138	2.5	2.4	0.00	0.53	1.00	Increasing trend virtually certain	2
Rotoma	TL-p	138	1.7	1.9	0.00	3.45	1.00	Increasing trend virtually certain	2
Rotoma	TLI	137	2.2	2.2	0.00	1.42	1.00	Increasing trend virtually certain	2
Rotoma	Chl-a (mg/m3)	138	1.2	1.1	0.11	0.54	0.95	Increasing trend possible	1
Rotoma	Clarity (m)	136	12.8	13.0	0.00	-1.71	1	Decreasing trend virtually certain	-2
Rotoma	TN (mg/m3)	138	106	103	0.00	0.97	1.00	Increasing trend virtually certain	2
Rotoma	TP (mg/m3)	138	3.8	3.6	0.00	5.02	1.00	Increasing trend virtually certain	2
Rotomahana	TL-c	138	3.7	3.7	0.02	-0.99	0.992	Decreasing trend very likely	-2
Rotomahana	TL-s	139	3.6	3.6	0.32	-0.20	0.851	Decreasing trend possible	0
Rotomahana	TL-n	139	3.3	3.3	0.13	0.24	0.933	Increasing trend possible	1
Rotomahana	TL-p	138	4.2	4.1	0.48	0.21	0.763	Increasing trend about as likely as not	0
Rotomahana	TLI	137	3.7	3.7	0.05	-0.33	0.975	Decreasing trend likely	-1
Rotomahana	Chl-a (mg/m3)	138	4.5	3.9	0.02	-2.60	0.992	Decreasing trend very likely	-2
Rotomahana	Clarity (m)	139	5.1	5.0	0.32	0.51	0.841	Increasing trend possible	0
Rotomahana	TN (mg/m3)	139	197	191	0.13	0.60	0.933	Increasing trend possible	1
Rotomahana	TP (mg/m3)	138	25.3	22.2	0.48	0.59	0.763	Increasing trend about as likely as not	0
Rotorua	TL-c	137	4.8	4.8	0.31	-0.28	0.855	Decreasing trend possible	0
Rotorua	TL-s	137	4.3	4.3	0.12	-0.24	0.947	Decreasing trend possible	-1
Rotorua	TL-n	137	3.9	3.9	0.53	0.13	0.738	Increasing trend about as likely as not	0
Rotorua	TL-p	137	3.8	3.8	0.03	0.85	0.99	Increasing trend very likely	2
Rotorua	TLI	137	4.2	4.2	0.82	0.04	0.589	Trend unlikely	0
Rotorua	Chl-a (mg/m3)	137	11.7	10.5	0.31	-1.46	0.855	Decreasing trend possible	0
Rotorua	Clarity (m)	137	3.0	2.9	0.12	0.76	0.942	Increasing trend possible	1
Rotorua	TN (mg/m3)	137	323	313	0.53	0.39	0.738	Increasing trend about as likely as not	0
Rotorua	TP (mg/m3)	137	18.5	16.6	0.03	2.21	0.99	Increasing trend very likely	2
Tarawera	TL-c	137	2.6	2.6	0.48	0.00	0.773	Decreasing trend about as likely as not	0
Tarawera	TL-s	136	2.9	2.9	0.51	-0.13	0.759	Decreasing trend about as likely as not	0
Tarawera	TL-n	136	2.3	2.3	0.73	0.08	0.634	Trend unlikely	0
Tarawera	TL-p	136	3.2	3.1	0.93	0.00	0.534	Trend extremely unlikely	0
Tarawera	TLI	135	2.7	2.7	0.59	-0.09	0.722	Decreasing trend about as likely as not	0
Tarawera	Chl-a (mg/m3)	137	1.6	1.4	0.48	0.00	0.773	Decreasing trend about as likely as not	0
Tarawera	Clarity (m)	136	8.5	8.6	0.51	0.29	0.746	Increasing trend about as likely as not	0
Tarawera	TN (mg/m3)	136	91	90	0.73	0.14	0.634	Trend unlikely	0
Tarawera	TP (mg/m3)	136	11.7	9.9	0.93	0.00	0.534	Trend extremely unlikely	0
Tikitapu	TL-c	137	2.9	2.9	0.08	0.70	0.96	Increasing trend likely	2
Tikitapu	TL-s	131	3.2	3.1	0.41	0.53	0.796	Increasing trend about as likely as not	1
Tikitapu	TL-n	137	3.1	3.1	0.00	0.50	1.00	Increasing trend virtually certain	2
Tikitapu	TL-p	137	2.3	2.3	0.12	0.00	0.946	Decreasing trend possible	-1
Tikitapu	TLI	137	2.8	2.9	0.22	0.30	0.888	Increasing trend possible	1
Tikitapu	Chl-a (mg/m3)	137	2.1	1.9	0.08	1.76	0.96	Increasing trend likely	2
Tikitapu	Clarity (m)	131	7.1	7.1	0.41	-1.17	0.809	Decreasing trend about as likely as not	-1
Tikitapu	TN (mg/m3)	137	172	168	0.00	1.18	1.00	Increasing trend virtually certain	2
Tikitapu	TP (mg/m3)	137	5.3	5.0	0.12	0.00	0.946	Decreasing trend possible	-1
Rotoiti Okawa Bay	TL-c	138	4.4	4.4	0.00	1.54	1.00	Increasing trend virtually certain	2
Rotoiti Okawa Bay	TL-s	130	4.2	4.2	0.18	0.50	0.912	Increasing trend possible	1
Rotoiti Okawa Bay	TL-n	139	3.9	3.8	0.00	0.83	1.00	Increasing trend virtually certain	2
Rotoiti Okawa Bay	TL-p	139	4.7	4.6	0.02	0.69	0.99	Increasing trend very likely	2
Rotoiti Okawa Bay	TLI	138	4.3	4.2	0.00	0.98	1.00	Increasing trend virtually certain	2
Rotoiti Okawa Bay	Chl-a (mg/m3)	138	10.0	7.3	0.00	5.02	1.00	Increasing trend virtually certain	2
Rotoiti Okawa Bay	Clarity (m)	130	3.2	3.0	0.18	-1.67	0.919	Decreasing trend possible	-1
Rotoiti Okawa Bay	TN (mg/m3)	139	335	290	0.00	2.59	1.00	Increasing trend virtually certain	2
Rotoiti Okawa Bay	TP (mg/m3)	139	39.2	32.3	0.02	2.35	0.99	Increasing trend very likely	2

Appendix E – CUSUM analysis for TLI components

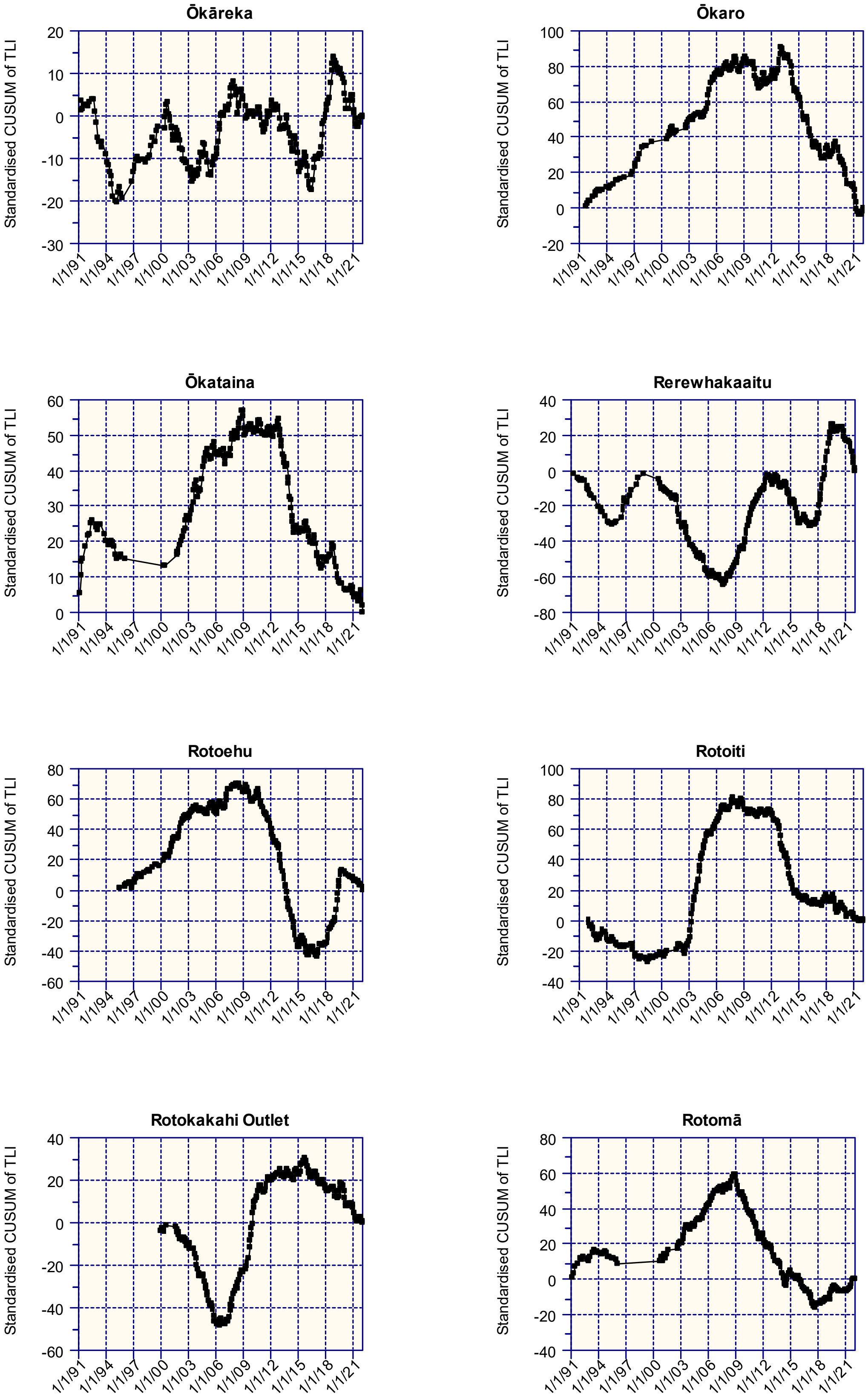


Figure E.1 a: *Standardise CUSUM graphs for the TLI. A straight line indicates no trend, an upward slope (A-shape) indicates an increasing trend, and a downward slope (U-shape) a decreasing trend.*

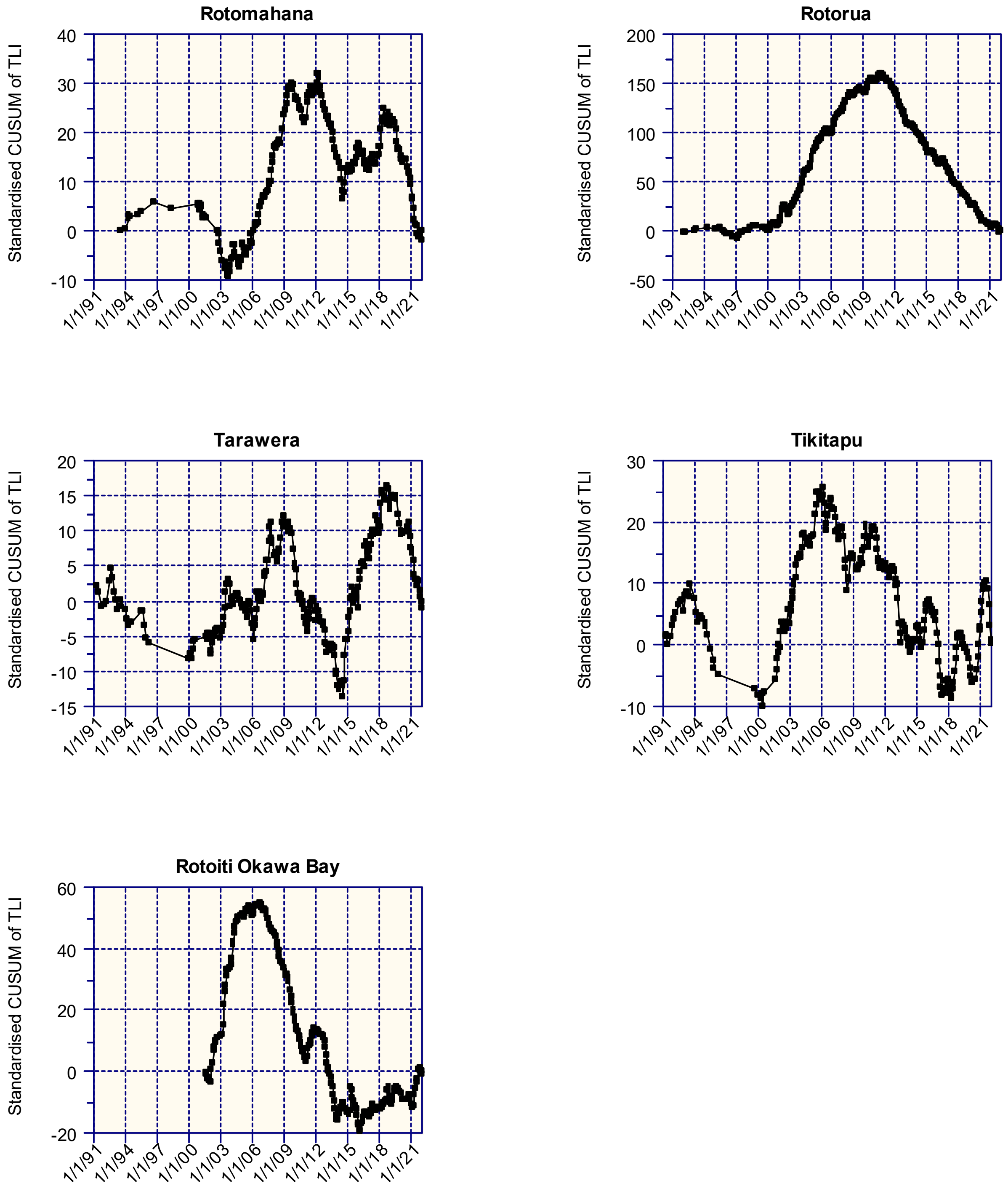
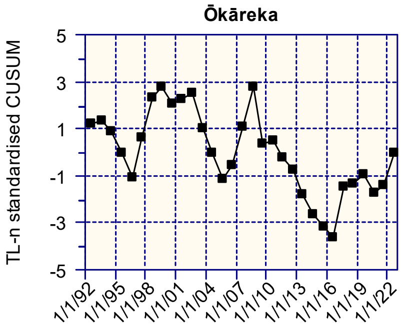
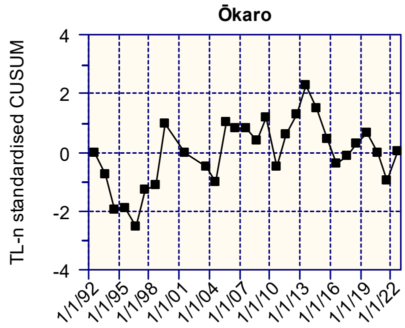
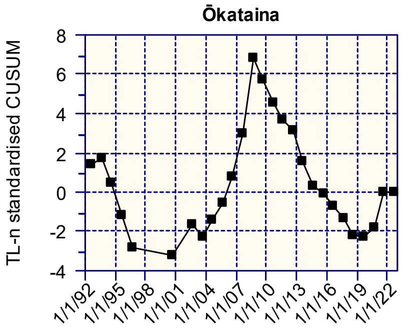


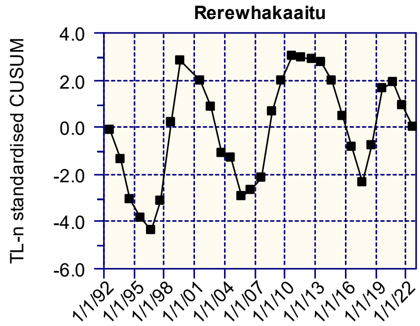
***Figure E.1 b**: Standardise CUSUM graphs for TLI. A straight line indicates no trend, an upward slope (A-shape) indicates an increasing trend, and a downward slope (U-shape) a decreasing trend.*

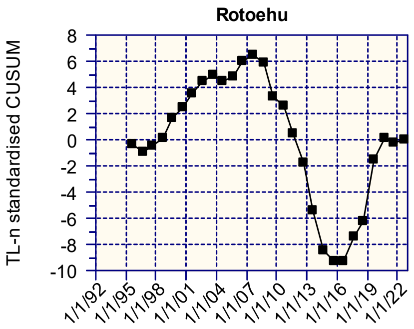
Standardised CUSUM of detrended data for TL-n, TP-p, TL-c and TL-s

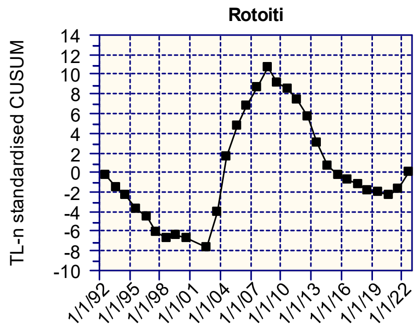


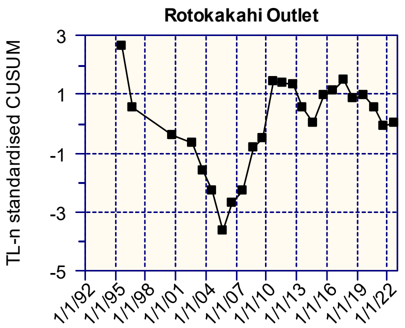


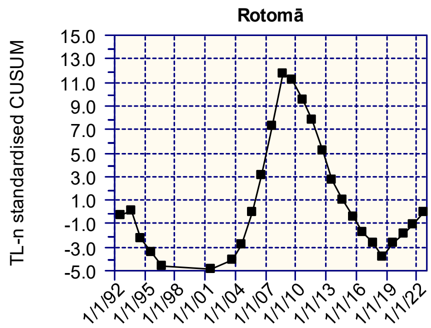


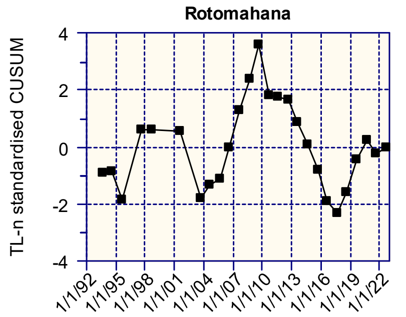


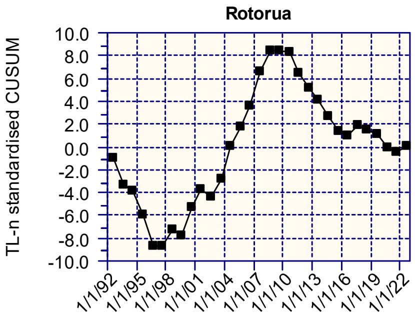









Rotomahana
TL-n standardised CUSUM
4
2
0
-2
-4
1/1/92
1/1/95
1/1/98
1/1/01
1/1/04
1/1/07
1/1/10
1/1/13
1/1/16
1/1/19
1/1/22


Rotorua
TL-n standardised CUSUM
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8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
1/1/92
1/1/95
1/1/98
1/1/01
1/1/04
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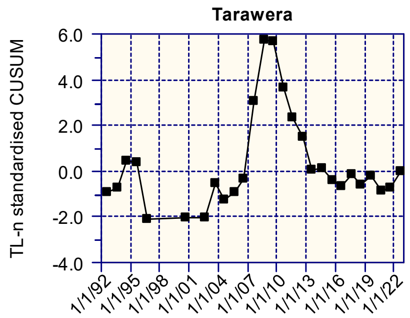
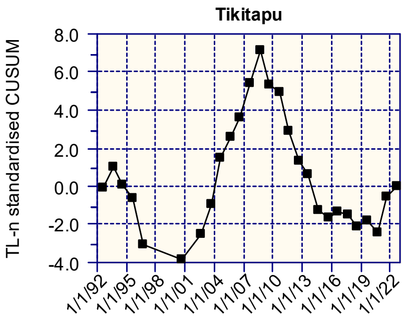
1/1/19
1/1/22


Tarawera
TL-n standardised CUSUM
6.0
4.0
2.0
0.0
-2.0
-4.0
1/1/92
1/1/95
1/1/98
1/1/01
1/1/04
1/1/07
1/1/10
1/1/13
1/1/16
1/1/19
1/1/22


Tikitapu
TL-n standardised CUSUM
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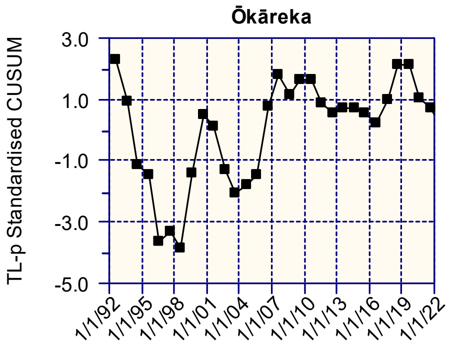
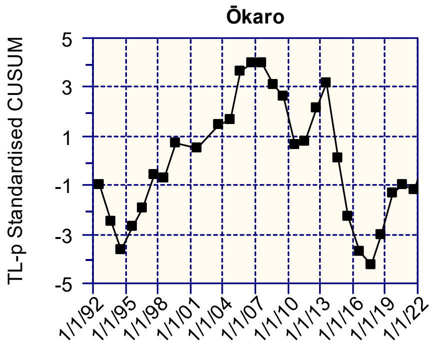
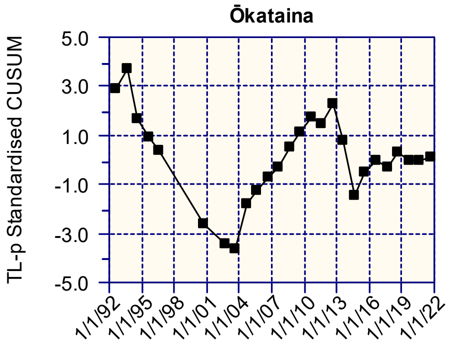
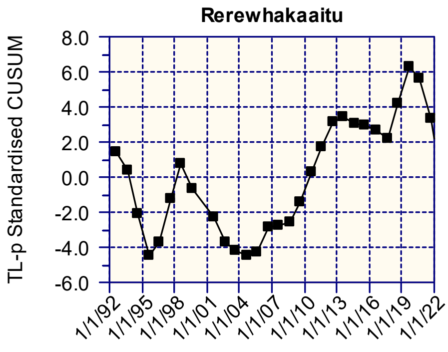
6.0
4.0
2.0
0.0
-2.0
-4.0
1/1/92
1/1/95
1/1/98
1/1/01
1/1/04
1/1/07
1/1/10
1/1/13
1/1/16
1/1/19
1/1/22


Ōkāreka
TL-p Standardised CUSUM


Ōkaro
TL-p Standardised CUSUM


Ōkataina
TL-p Standardised CUSUM


Rerewhakaaitu
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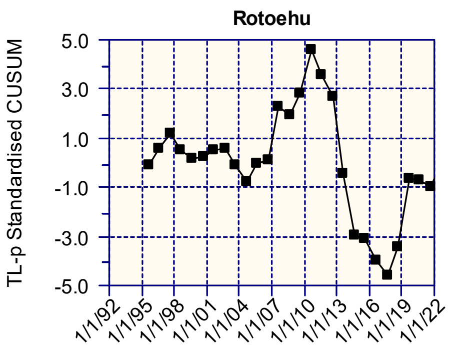
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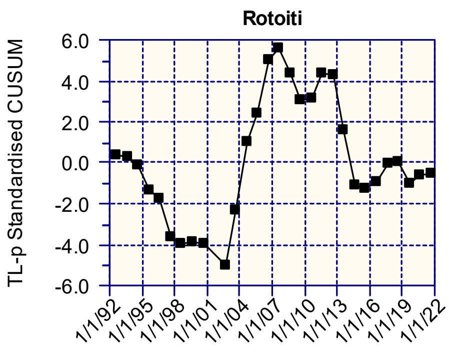
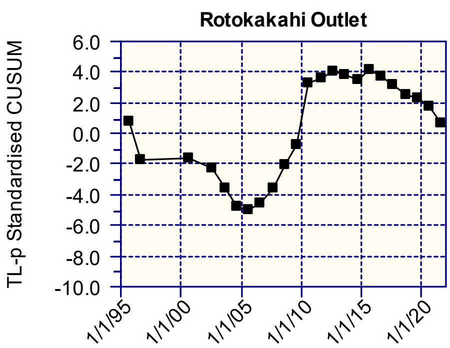
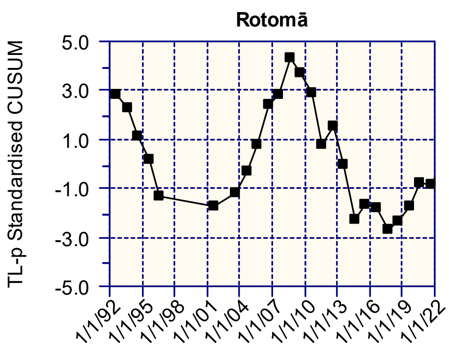
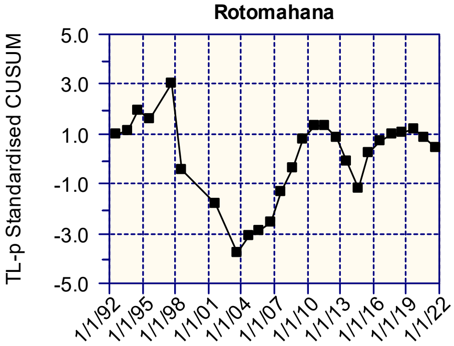
TL-p Standardised CUSUM


Rotoiti
TL-p Standardised CUSUM


Rotokakahi Outlet
TL-p Standardised CUSUM


Rotomā
TL-p Standardised CUSUM


Rotomahana
TL-p Standardised CUSUM
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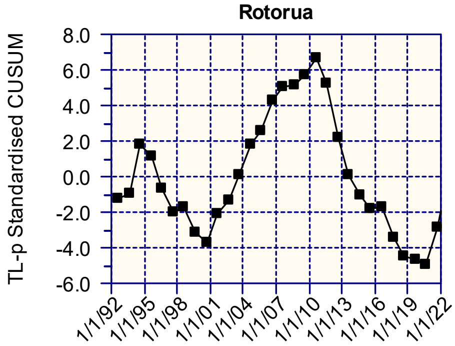
1/1/22


Rotorua
TL-p Standardised CUSUM
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1/1/95
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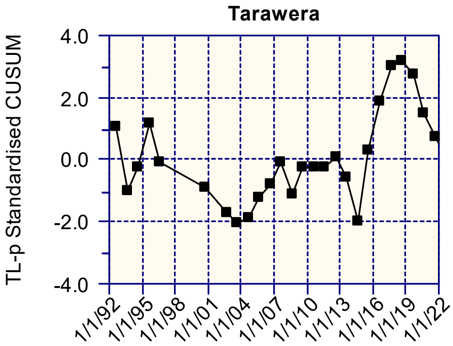
1/1/22


Tarawera
TL-p Standardised CUSUM
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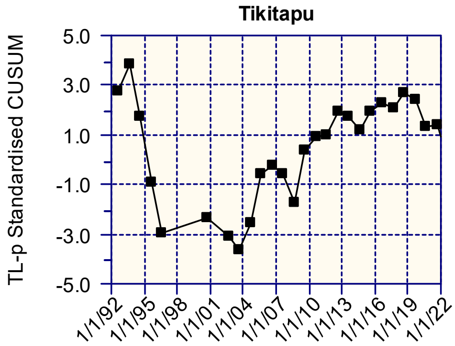
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-5.0
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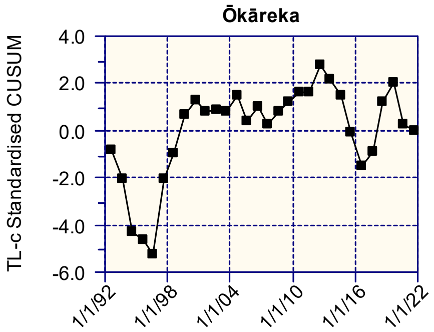
Ōkāreka
TL-c Standardised CUSUM
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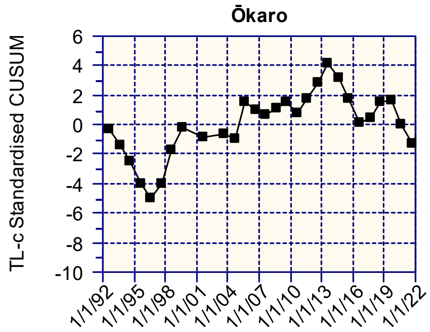
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TL-c Standardised CUSUM
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-4
-6
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-10
1/1/92
1/1/95
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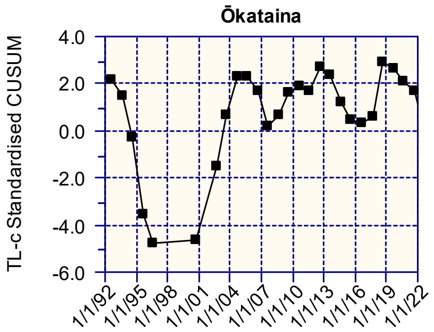
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TL-c Standardised CUSUM
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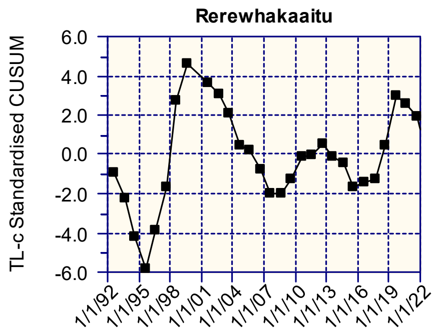
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TL-c Standardised CUSUM
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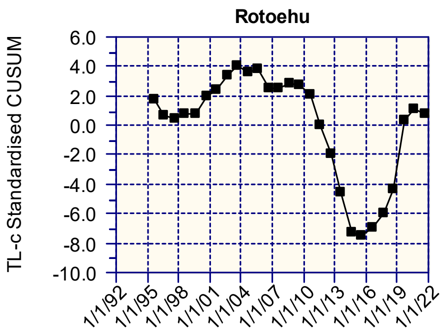
Rotoehu
TL-c Standardised CUSUM
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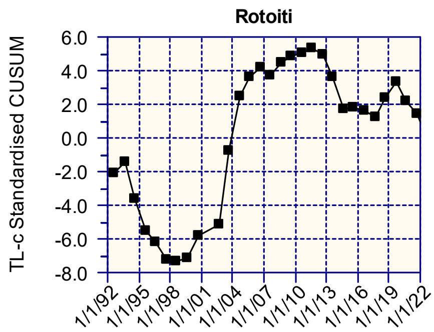
Rotoiti
TL-c Standardised CUSUM
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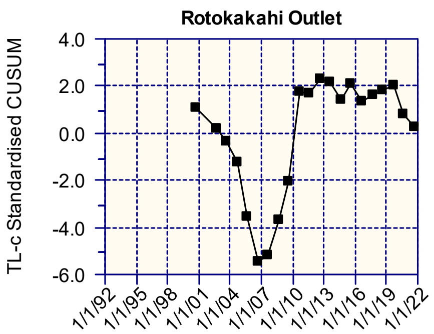
Rotokakahi Outlet
TL-c Standardised CUSUM
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0.0
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-4.0
-6.0
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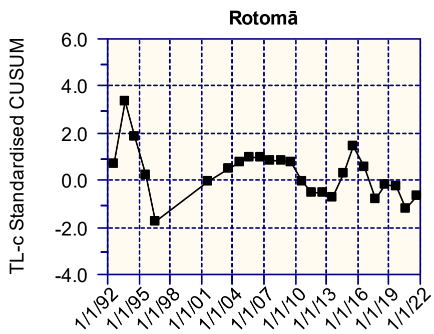
Rotomā
TL-c Standardised CUSUM
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2.0
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-2.0
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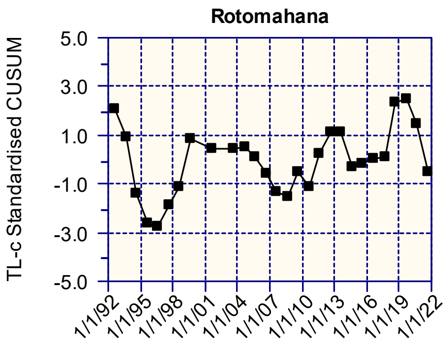
Rotomahana
TL-c Standardised CUSUM
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-5.0
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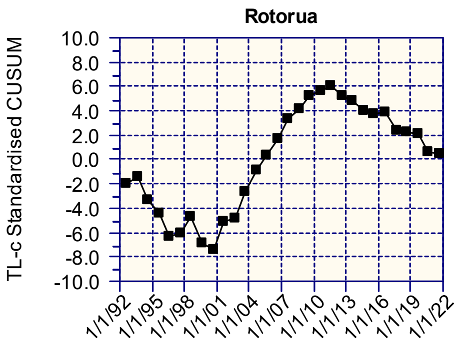
Rotorua
TL-c Standardised CUSUM
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1/1/95
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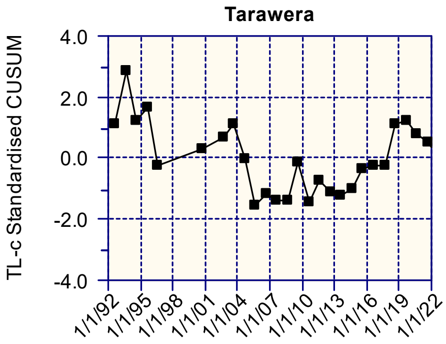
Tarawera
TL-c Standardised CUSUM
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-4.0
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1/1/95
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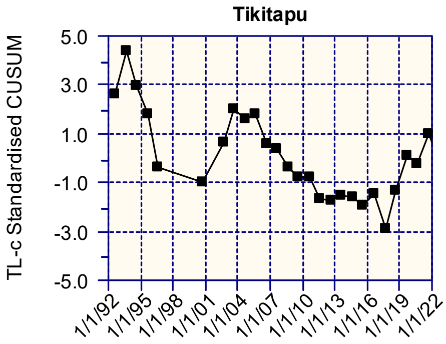
Tikitapu
TL-c Standardised CUSUM
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-5.0
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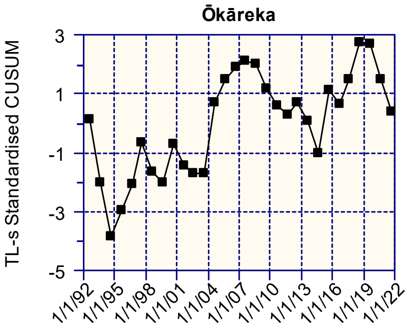
1/1/22


Ōkāreka
TL-s Standardised CUSUM
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-1
-3
-5
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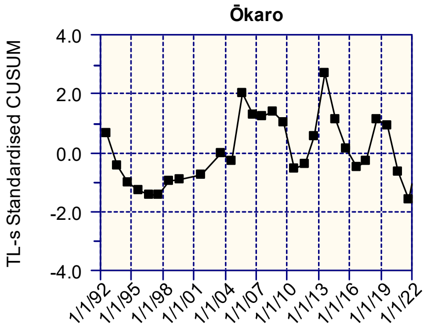
Ōkaro
TL-s Standardised CUSUM
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0.0
-2.0
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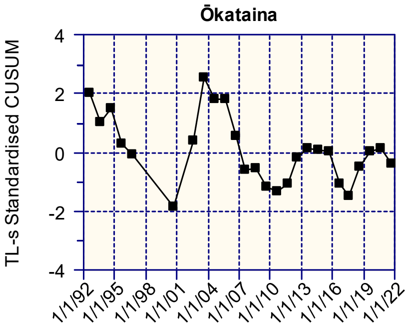
Ōkataina
TL-s Standardised CUSUM
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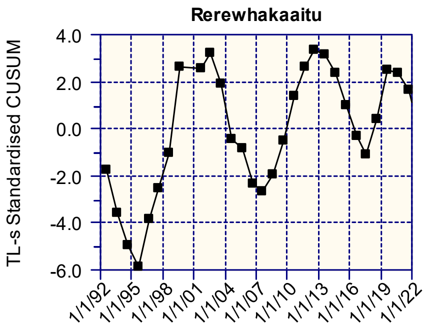
Rerewhakaaitu
TL-s Standardised CUSUM
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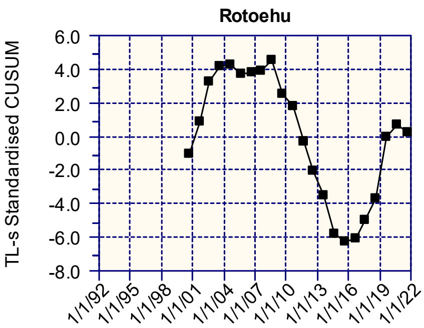
Rotoehu
TL-s Standardised CUSUM
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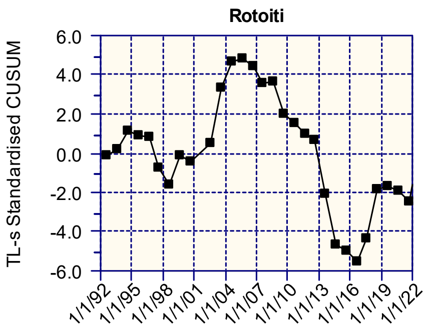
Rotoiti
TL-s Standardised CUSUM
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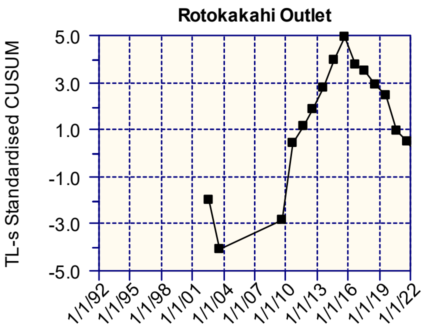
Rotokakahi Outlet
TL-s Standardised CUSUM
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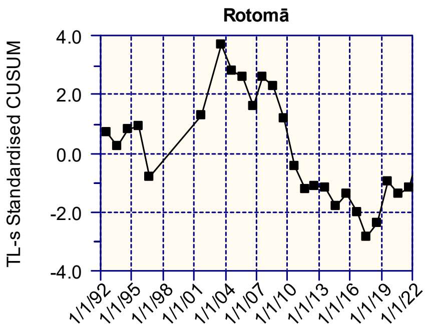
Rotomā
TL-s Standardised CUSUM
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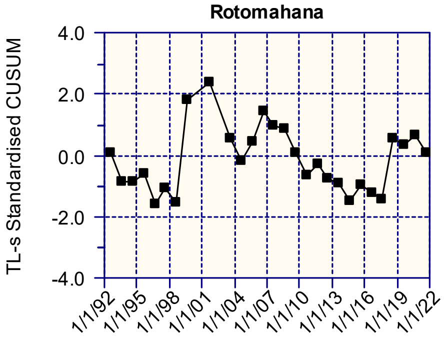
Rotomahana
TL-s Standardised CUSUM
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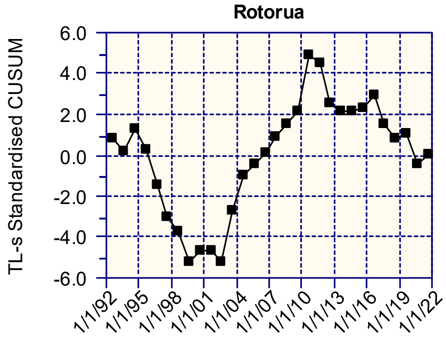
Rotorua
TL-s Standardised CUSUM
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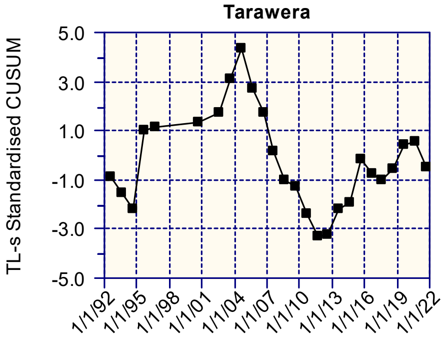
Tarawera
TL-s Standardised CUSUM
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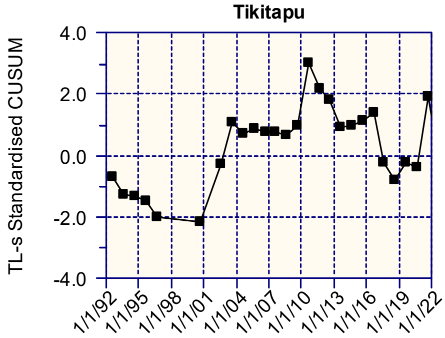
Tikitapu
TL-s Standardised CUSUM
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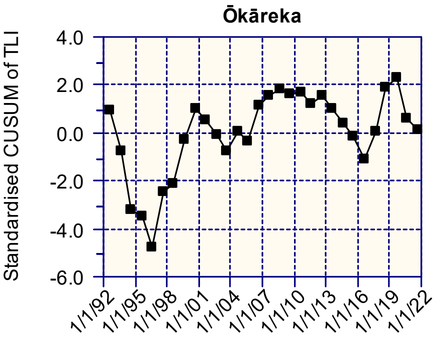
Ōkāreka
Standardised CUSUM of TLI
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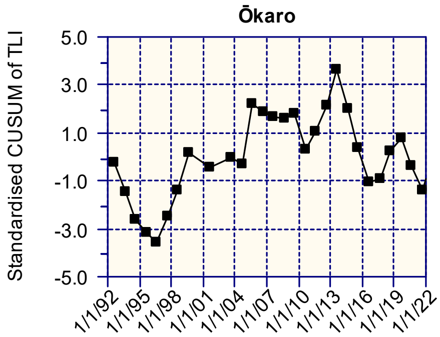
Ōkaro
Standardised CUSUM of TLI
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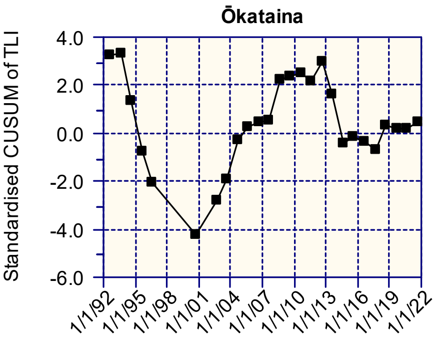
Ōkataina
Standardised CUSUM of TLI
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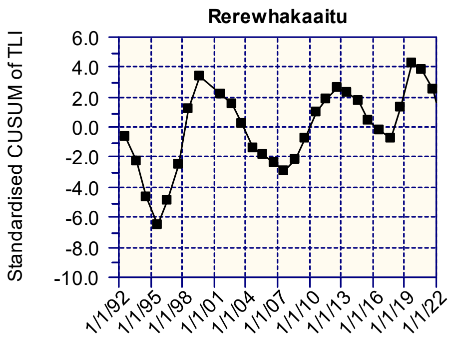
Rerewhakaaitu
Standardised CUSUM of TLI
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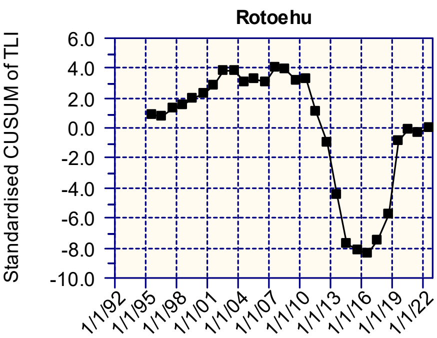
Rotoehu
Standardised CUSUM of TLI
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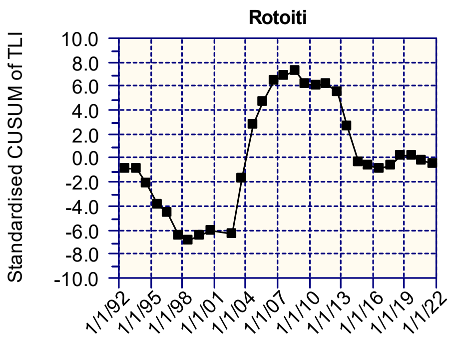
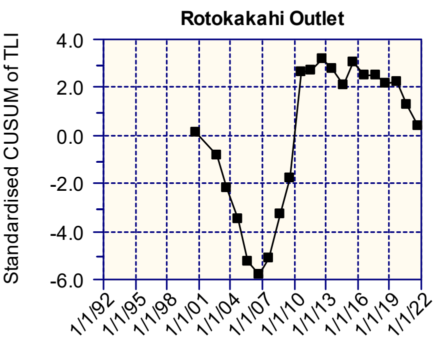
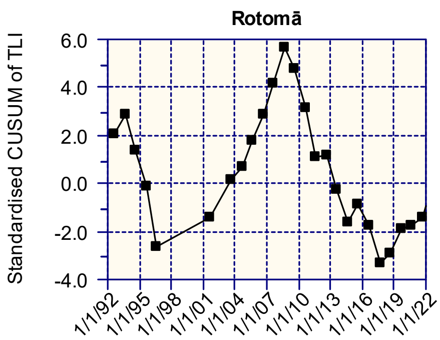
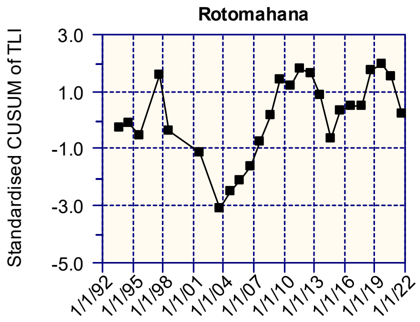
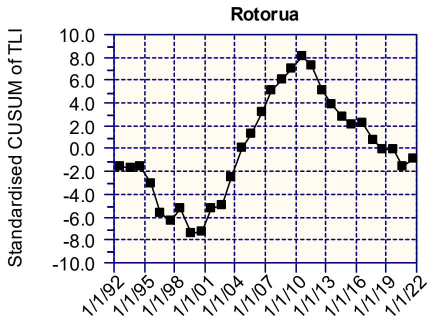

Rotoiti
Standardised CUSUM of TLI
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
1/1/92
1/1/95
1/1/98
1/1/01
1/1/04
1/1/07
1/1/10
1/1/13
1/1/16
1/1/19
1/1/22


Rotokakahi Outlet
Standardised CUSUM of TLI
4.0
2.0
0.0
-2.0
-4.0
-6.0
1/1/92
1/1/95
1/1/98
1/1/01
1/1/04
1/1/07
1/1/10
1/1/13
1/1/16
1/1/19
1/1/22

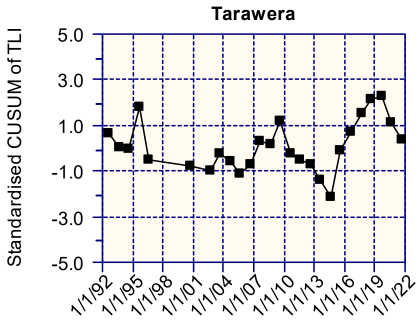

Rotomā
Standardised CUSUM of TLI
6.0
4.0
2.0
0.0
-2.0
-4.0
1/1/92
1/1/95
1/1/98
1/1/01
1/1/04
1/1/07
1/1/10
1/1/13
1/1/16
1/1/19
1/1/22



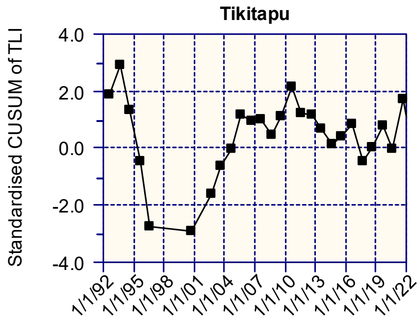
Rotomahana
Standardised CUSUM of TLI
3.0
1.0
-1.0
-3.0
-5.0
1/1/92
1/1/95
1/1/98
1/1/01
1/1/04
1/1/07
1/1/10
1/1/13
1/1/16
1/1/19
1/1/22



Rotorua
Standardised CUSUM of TLI
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
1/1/92
1/1/95
1/1/98
1/1/01
1/1/04
1/1/07
1/1/10
1/1/13
1/1/16
1/1/19
1/1/22



Tarawera
Standardised CUSUM of TLI
5.0
3.0
1.0
-1.0
-3.0
-5.0
1/1/92
1/1/95
1/1/98
1/1/01
1/1/04
1/1/07
1/1/10
1/1/13
1/1/16
1/1/19
1/1/22



Tikitapu
Standardised CUSUM of TLI
4.0
2.0
0.0
-2.0
-4.0
1/1/92
1/1/95
1/1/98
1/1/01
1/1/04
1/1/07
1/1/10
1/1/13
1/1/16
1/1/19
1/1/22