CAWTHRON

Identifying knowledge gaps to aid in managing three shallow coastal lakes in Southland

Cawthron Report 4075

World-class science
for a better future

REVIEWED BY: Georgia Thomson-Laing

APPROVED FOR RELEASE BY:
Roger Young

PROJECT NUMBER: 18665

ISSUE DATE: 11 November 2024

RECOMMENDED CITATION: Wood S, Kelly L, Schallenberg L, Shchapov K, Pearman J, Vandergoes M, Li X, Howarth J, Shepherd C, Waters S. 2024. Identifying knowledge gaps to aid in managing three shallow coastal lakes in Southland. Nelson: Cawthron Institute. Cawthron Report 4075. Prepared for Environment Southland.

Identifying knowledge gaps to aid in managing three shallow coastal lakes in Southland

Susie Wood,[a] Laura Kelly,[a] Lena Schallenberg,[a] Kirill Shchapov,[a] John Pearman,[a] Marcus Vandergoes,[b] Xun Li,[b] Jamie Howarth,[c] Claire Shepherd,[b] Sean Waters[d]

[a.] Cawthron Institute
[b.] GNS Science
[c.] Victoria University of Wellington
[d.] Parker Resolutionz Ltd

Prepared for Environment Southland

Contents

Executive summary

This report focuses on three shallow lakes in Murihiku Southland: Lake George / Uruwera, Lake Vincent and The Reservoir. The main objective was to identify knowledge gaps that need to be addressed to support the development of effective lake restoration plans. The report synthesises existing reports, data from Environment Southland's monitoring efforts, and data from the national lakes research programme 'Our lakes' health: past, present, future.'

The analysis of water quality data indicates that all three lakes are currently eutrophic. A 5-year trends analysis for Lake George / Uruwera indicated that most water quality attributes were 'likely degrading'. There was insufficient data to undertake trend analyses for Lake Vincent and The Reservoir. A visual inspection of the data revealed high levels of variability, reinforcing the need for more frequent and long-term monitoring. One positive observation was that although cyanobacteria were present in all lakes, they were relatively low in abundance and common bloom-forming taxa were only present at very low levels.

Analysis of a single surface sediment sample from Lake Vincent (collected January 2019) indicated a high likelihood of internal phosphorus cycling. A paleolimnological analysis of the Lake Vincent sediment core showed rapid deforestation after Māori settlement, leading to increases in wetland species and minor shifts in aquatic bacterial communities. Following European settlement, there was a further decline in native vegetation. Despite these changes, the lake likely remained in an oligotrophic to mesotrophic state, with low levels of chlorophyll-*a*. The increase in wetland plants may have mitigated some impacts of deforestation.

The information in the report provides insight into the lake's nutrient sources and dynamics, but there are significant data gaps, which make developing restoration plans challenging. We recommend the following:

- Continue water quality monitoring and consider reducing the monitoring sites to one per lake to save resources. Bird surveys could be undertaken during monitoring to estimate the nutrient loads from bird excreta.
- Install monitoring buoys at Lake Vincent and The Reservoir with temperature, dissolved oxygen and pH sensors to improve understanding of oxygen and pH dynamics in the lake.
- Conduct one-off sediment geochemistry investigations to determine the likelihood of nutrient release from sediments during anoxic or high pH events.
- Update the CLUES modelling to estimate external loads for the three lakes.
- Develop water balance models specific to each lake, incorporating surface and groundwater data such as inflows / outflows, surface and groundwater connectivity, direct rain inputs, evapotranspiration and lake level.
- Conduct macrophyte monitoring (LakeSPI) at least once every 5 years, and one-time seasonal surveys of macrophyte biovolume to determine the degree to which macrophyte die-back contributes to lake anoxia cycles.
- Undertake biodiversity surveys to explore the presence of non-native and native species.

1. Introduction

Lake ecosystems in Aotearoa New Zealand are under significant pressure due to anthropogenic activities, including land-use change and the introduction of non-native species. These pressures are particularly acute for shallow lowland lakes. Shallow lowland lake ecosystems have considerable ecological, cultural and economic value, and in Murihiku Southland, they are important habitats for a range of taonga (treasured) species, including kākahi (freshwater mussel), macrophytes and native fish.

Regional management decisions aimed at restoration activities require the synthesis of multiple sources of data and information. These data include routine state of the environment (SOE) monitoring, specific event-based monitoring and national-scale projects, including programmes such as Our lakes' health: past, present, future (also known as Lakes380). In Murihiku Southland, routine SOE monitoring is undertaken at three shallow lowland lakes: Lake George / Uruwera, Lake Vincent and The Reservoir. Preliminary analysis of existing data indicates that the water quality of these lakes is declining, thus there is strong interest in developing restoration plans.

An essential first step in the development of a restoration plan is to establish a clear understanding of the current knowledge and data, and identify gaps that require further monitoring and sampling. To aid with restoration plan development, the Cawthron Institute was commissioned to:

- Collate and analyse available data from Lake George / Uruwera, Lake Vincent and The Reservoir.
- Identify data or knowledge gaps that limit the development of robust restoration plans.

To achieve these aims, we reviewed previous reports that include information on these three lakes. We then analysed monitoring data provided by Environment Southland and Land and Water Aotearoa (LAWA) to generate summaries of the data extent, current state and, where possible, trends. Lake George / Uruwera and Lake Vincent were included in the Lakes380 programme and summaries of these data were also compiled. In this report, we identify and discuss additional data and the information needed to create robust restoration plans.

2. Study lakes

2.1 Lake George / Uruwera

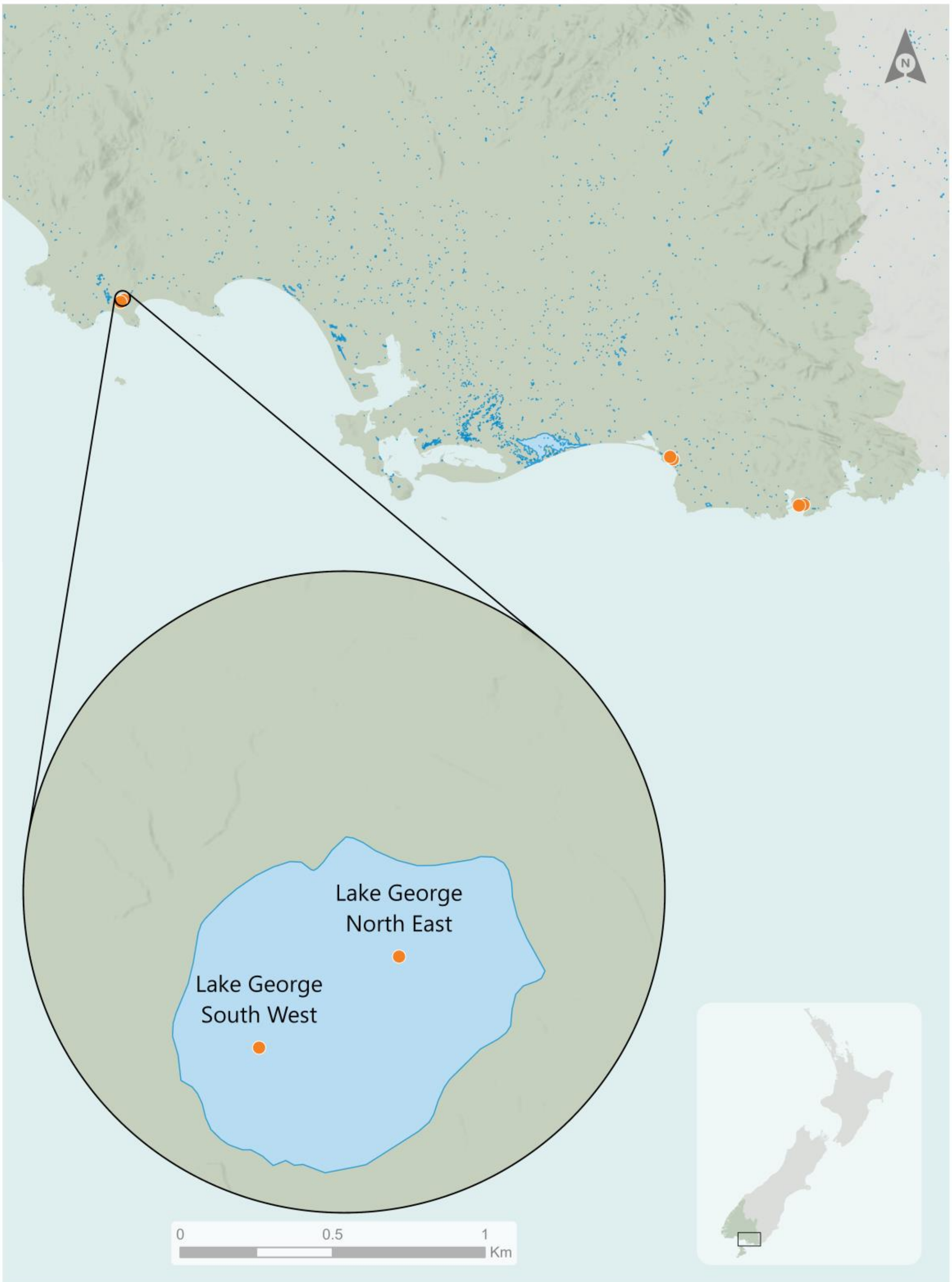
Lake George / Uruwera is a shallow coastal dune lake located near Colac Bay / Oraka on the south coast of Murihiku Southland within the Lake George / Uruwera Wildlife Reserve (Figure 1; Table 1). Its catchment area includes protected lands such as the Longwood Mountains and the Owen Conservation Project, as well as pasture and fringing wetlands. The lake was affected by historical gold mining activities in its catchment, which led to significant sediment infilling of the lakebed. However, the more recent protection of the surrounding land has facilitated the regeneration of native vegetation. The lake is a stronghold for giant kōkopu (Schallenberg and Kelly 2012). It experiences a high flushing rate with a short theoretical water residence time of 19 days, suggesting a strong susceptibility to catchment-scale activities that mobilise sediment and nutrients.

Table 1. Morphometric, hydrological and catchment data for the three study lakes.

Data type	Lake George / Uruwera	The Reservoir	Lake Vincent
Altitude (m.a.s.l)	10	13	19
Lake area (ha)	90.8	35.5	17.2
Maximum depth (m)	0.8#	5.0$	6.3#
Lake volume* (m^2)	286,801	592,115	286,801
Residence time* (days)	19	55	49
Catchment area$ (km^2)	29.12	5.73	3.14
Nitrogen loading$ (T/y)	17.0	2.0	6.0
Phosphorus loading$ (T/y)	0.76	0.20	0.05
Catchment % pasture$	50	66	91
Catchment % natural$	43	34	6

Measured during the Lakes380 programme.
* Estimates as calculated in the Freshwater Ecosystems New Zealand (FENZ) database (Leathwick et al. 2010).
$ Data from Schallenberg and Kelly (2012).

Lake George | Southland



Back ground layers: Eagle Technology, LINZ (Land

Figure 1. Location of Lake George / Uruwera. The two in-lake monitoring sites are labelled by the orange points, along with a monitoring site on one of the inflows. The scale bar refers to the map contained within the inset circle.

2.2 The Reservoir

The Reservoir is a shallow lake situated near Slope Point and Haldane Bay (Figure 2). It was formed from the damming of a small coastal creek, although the lake's outlet is not controlled. While the upper parts of the catchment are largely indigenous forests, the lower parts are primarily characterised by intensive agricultural activities, particularly dairy farming (Table 1). The limited inflows to the lake result in a predicted water residence time of 55 days, indicating that the lake's water quality and ecology are influenced to some extent by in-lake processes.

Figure 2. Location of The Reservoir. The two in-lake monitoring sites are labelled by the orange points. The scale bar refers to the map contained within the inset circle.

2.3 Lake Vincent

Lake Vincent is a shallow coastal dune lake situated between the Mataura River mouth and Waipapa Point (Table 1; Figure 3). It is fed by a relatively small catchment dominated by high-productivity grassland. The lake receives limited freshwater inflows, resulting in a predicted water residence time of 49 days (Table 1); this indicates that the lake's internal processes may play a significant role in shaping its water quality and ecological conditions.

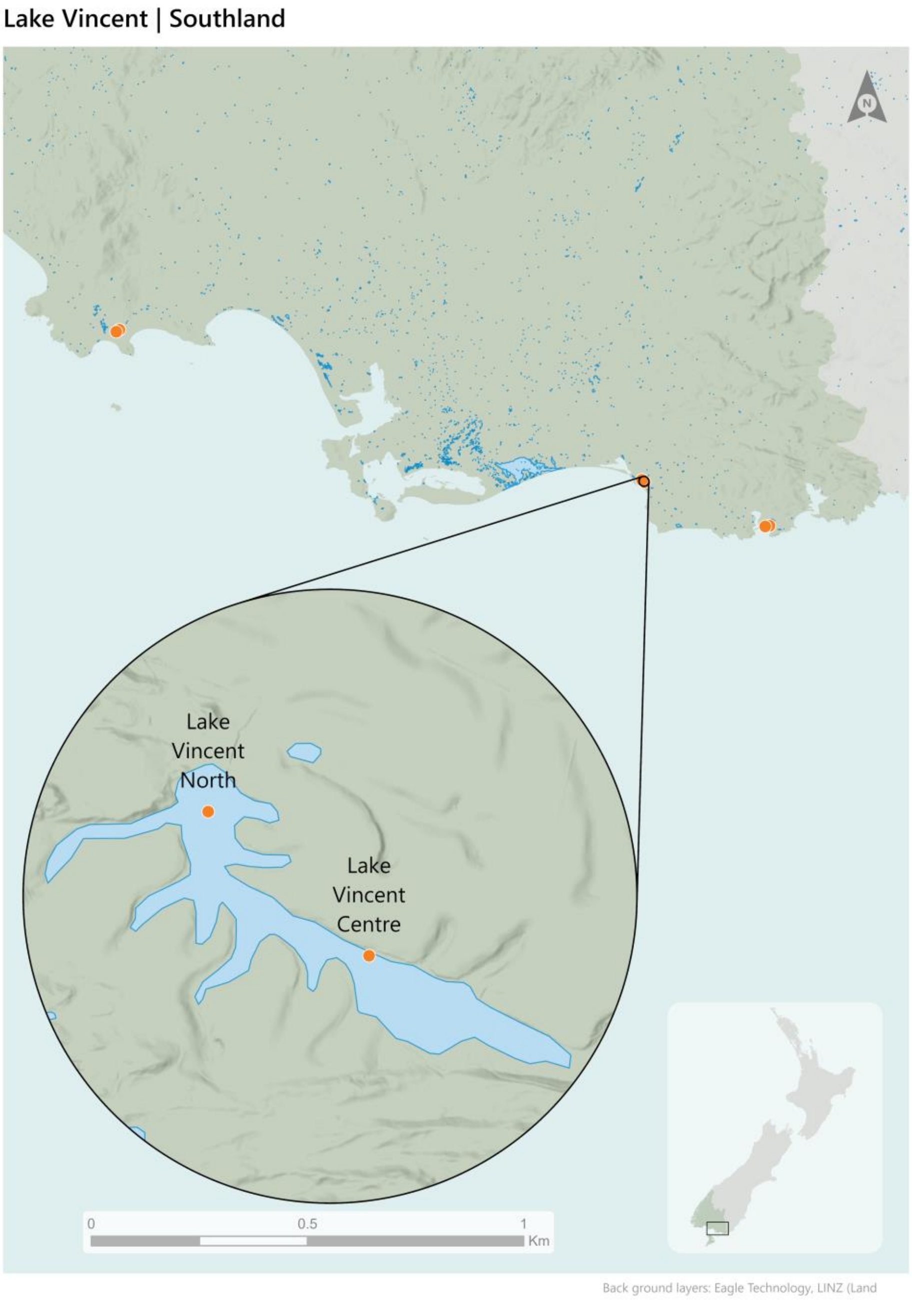


Figure 3. Location of Lake Vincent. The two in-lake monitoring sites are labelled by the orange points. The scale bar refers to the map contained within the inset circle.

3. Review of relevant information in existing reports

For this review, we identified three reports that contain information of relevance: Schallenberg and Kelly (2012); Kelly et al. (2013); Schallenberg and Kelly (2013). These reports broadly address the ecological state of the three focal lakes between 2000 and 2012, covering the impact of nutrient loading as well as the data gaps that influence nutrient loading models and estimates of lake reference conditions. Relevant sections of the reports are summarised below.

3.1 Ecological state

Schallenberg and Kelly (2012) assessed the water quality and ecological condition of six shallow Southland lakes, including Lake George / Uruwera, Lake Vincent and The Reservoir. They gathered data from three sources: (1) an Aotearoa New Zealand-wide survey of the ecological integrity of shallow coastal lakes conducted from 2004 to 2008; (2) water quality data collected by Environment Southland between 2000 and 2007; and (3) a survey carried out in 2012. They ranked all three lakes as having moderate ecological integrity, with Lake George / Uruwera ranking slightly higher than Lake Vincent and The Reservoir. Their key findings are outlined below.

Lake Georga/Uruwera

Schallenberg and Kelly (2012) highlighted that Lake George / Uruwera had a very short water residence time, which likely prevented the proliferation of phytoplankton. Based on the water quality variables collected in 2004 and 2012, they described the lake as eutrophic. They noted that it had relatively high turbidity and a shallow euphotic depth. It was the only lake in their study to contain the native water flea *Daphnia carinata*, which may also play an important role in regulating phytoplankton biomass in the lake. Of the shallow lakes surveyed in the authors' 2004–08 national study, Lake George / Uruwera was the only lake to contain this species. They observed a significant decrease in total nutrients between 2000 and 2004, with total phosphorus (TP) reducing from 74 ug/L to 33 ug/L and total nitrogen (TN) decreasing from 1,100 ug/L to 460 ug/L, although the authors did not specify the cause. The macrophyte beds in Lake George / Uruwera were sparse, which they concluded was likely normal due to its large fetch and exposure to winds; however, no non-native macrophytes were present. *Echyridella menziesii* (kākahi) were present, as were long and shortfin eel and the common bully. The authors also recorded the presence of the non-native species European perch.

Lake Vincent

Schallenberg and Kelly (2012) described Lake Vincent as oligotrophic to eutrophic, as TN in the lake was high (at a eutrophic level) when sampled in 2004 and 2012, while phytoplankton biomass was exceptionally low (chlorophyll-*a* was at an oligotrophic level). Although nitrate levels in the lake were quite high (24.1 ug/L in 2004 and 51 ug/L in 2012), phosphorus availability was low (TP: 14.7 ug/L in 2004 and 19 ug/L in 2012), potentially limiting phytoplankton growth. The report suggested that the low phosphorus levels make this lake particularly vulnerable to intensifying land use. The authors found an unusual cladoceran (a bosminid) in the 2012 samples, which they suggested might be a variant or sub-species of the common *Bosmina meridionalis*. About 86% of the lake was covered in macrophytes, likely conferring some resilience to the effects of eutrophication, although the non-native species *Elodea canadensis* was present. Lake Vincent had a high diversity of invertebrates, including kākahi. Long and shortfin eel were also present, as was the critically declining giant kōkopu. Unfortunately, non-native perch were detected. Snails, worms, chironomids and amphipods dominated the macrobenthic communities of Lake Vincent.

The Reservoir

Based on the data collected in 2012, Schallenberg and Kelly (2012) described The Reservoir as eutrophic, with a high phytoplankton biomass (chlorophyll-*a* was 10.3 ug/L in 2004 and 20 ug/L in 2012), dominated by the large desmid *Staurastrum*. The lake's macrophyte communities were sparse, covering only about 10% of the lake, and included the non-native macrophyte species *Elodea canadensis*. Long and shortfin eel and giant kōkopu were present in The Reservoir, and similar to Lake Vincent, the macrobenthic communities were dominated by snails, worms, chironomids and amphipods.

3.2 Nutrient loading

The National Policy Statement for Freshwater Management (NPS-FM 2020; MfE 2024) has led regional authorities, including Environment Southland, to consider nutrient load limits for shallow coastal lakes due to their susceptibility to degradation from land-use intensification. Kelly et al. (2013) undertook a literature review on nutrient loading and used a modelling approach to assess nutrient loading for lakes in Murihiku Southland and the South Island. The report noted that maintaining optimal phosphorus levels is essential for preserving ecological integrity, as emphasised by overseas research on both external and internal nutrient origins. Phosphorus loading affects benthic communities, and the results of Kelly et al. (2013) highlighted lower thresholds for lakes in Aotearoa New Zealand compared to those reported in international studies. The findings advocate for cautious nutrient loading objectives to mitigate biodiversity decline and thus meet preferred water quality standards. Further validation of loading data was advised to improve the precision of annual load predictions. The results are complex, and only a few of the findings specific to the focal lakes are summarised below. Readers are referred to the full report for an in-depth understanding of the approaches used and the complete set of results.

Based on the Catchment Land Use for Environmental Sustainability (CLUES) modelling, Kelly et al. (2013) suggested that Lake George / Uruwera and The Reservoir had nutrient ratios close to nutrient thresholds (i.e. TN:TP = 14; dissolved inorganic nitrogen [DIN]:TP = 1), suggesting that they are likely to be co-limited by both nitrogen and phosphorus. Lake Vincent had TN:TP ratios indicative of stronger phosphorus limitation. All three lakes fitted the phosphorus-loading chlorophyll-*a* model reasonably well, suggesting phosphorus loading is likely to be an important controller of chlorophyll-*a* biomass in these lakes. The authors, however, noted that inferring nutrient limitation is complex, and ratios are likely to fluctuate throughout the year as processing and internal loading rates vary seasonally with changes in water temperature and other factors.

3.3 Estimates of reference conditions

The report 'Estimates of reference conditions for Southland's shallow, lowland lakes' by Schallenberg and Kelly (2013) focused on determining the reference conditions of Southland lakes based on a framework of ecological integrity. The report used indicators across three components: nativeness, pristineness and resilience. Thresholds defining reference conditions were derived from analysis of mid-to-late summer data for lowland shallow lakes in Aotearoa New Zealand. Nativeness conditions were calculated as percentage departures from those conditions found in reference lakes (i.e. reference lakes were at 100%). Pristineness indicators were largely physico-chemical variables relating to nutrient enrichment, provided as thresholds for 'strict' or 'relaxed' reference condition lakes.

The lakes' nativeness was determined by the percentage of native fish, native macrophyte species and native macrophyte cover. For the three focal lakes, the fish nativeness indicator was 100% for The Reservoir, while Lake Vincent and Lake George / Uruwera contained perch and had lower percentages of 80% and about 68%, respectively. The Reservoir and Lake Vincent contained the non-native macrophyte *Elodea canadensis* and *Ranunculus trichophyllus*, resulting in a macrophyte nativeness indicator of around 75%; but both of these macrophyte species were absent in Lake George / Uruwera, giving it a score of 100%. Overall, The Reservoir, Lake Vincent and Lake George / Uruwera departed from the 'nativeness' reference condition by approximately 97%, 58% and 33%, respectively.

Indicators of pristineness were TN, TP, trophic level index (TLI), chlorophyll-*a* and CLUES nitrogen loadings from the catchment. Lake George / Uruwera exceeded both the strict and relaxed reference conditions for TN and TP. Lake Vincent and The Reservoir exceeded the strict reference condition threshold for TN and TP, with The Reservoir also slightly exceeding the relaxed conditions. Based on TLI levels, The Reservoir exceeded both the strict and relaxed reference condition thresholds, with Lake Vincent slightly exceeding the strict reference condition threshold. Chlorophyll-*a* concentrations in The Reservoir and Lake George / Uruwera exceeded both reference condition thresholds, whereas Lake Vincent's chlorophyll-*a* values were below the reference condition thresholds. The CLUES estimates of nitrogen loading showed that Lake Vincent was substantially above the reference threshold, while The Reservoir just slightly exceeded it. Lake George / Uruwera was below the threshold.

Of the available indicators for ecological resilience, Schallenberg and Kelly (2013) used the DIN:TP ratio, which is an indicator of the availability of nitrogen and phosphorus for phytoplankton. The authors defined a DIN:TP range and an upper threshold for reference lakes. They found that Lake George / Uruwera and The Reservoir were below the DIN:TP reference condition bottom threshold, meaning that there is higher TP and lower DIN than reference condition lakes. In contrast, Lake Vincent fell within the reference condition limits. The report concluded with an order of the lakes from high to low ecological integrity: 1) Lake George / Uruwera, 2) Lake Vincent, and 3) The Reservoir.

4. State of the environment data

4.1 Overview of datasets

The three lakes each have SOE monitoring data available from two in-lake locations. Some additional data exists for the inflow of Lake George / Uruwera (Lake George / Uruwera – Creek at Orepuki-Riverton Highway), the outflow of Lake Vincent, The Reservoir tributary at Haldane Bay, and The Reservoir outflows at Haldane Bay and 100 m downstream of The Reservoir (Figures 1, 2 and 3).

The datasets, which span from April 2012 to August 2023, contain approximately monthly discrete water quality and cyanobacterial data, and continuous water level and temperature data for some of the inflows / outflows. Data frequency and consistency increased over the period, with more frequent data available for the 5 years from 2019 to 2023.

It was not appropriate to analyse all of the water chemistry data, as some of these data co-vary (e.g. multiple nitrogen species); therefore, a sub-set of the attributes (detailed in Table 2) was chosen a priori to undergo formal analysis.

Table 2. Attributes used for data analysis of Lake George / Uruwera, Lake Vincent and The Reservoir. The data are given for each lake and site, including the month and year of the earliest and last available measurements in the dataset provided. nMeas is the total number of measurements for that attribute in the dataset.

Site name	Attributes	Start date–End date	nMeas
Lake George / Uruwera Creek at Orepuki-Riverton Highway	Chlorophyll-*a*	Apr 2012–Nov 2021	4
	Escherichia coli	July 2014–July 2023	81
	Nitrate nitrite	Apr 2012–July 2023	100
	Total nitrogen	Apr 2012–July 2023	100
	Dissolved reactive phosphorus	Apr 2012–July 2023	99
	Total phosphorus	Apr 2012–July 2023	100
	Turbidity (Lab FNU)	June 2018–July 2023	59
	Water temperature	Sept 2016–Aug 2023	356,526
	Ammoniacal nitrogen (adjusted)	Apr 2013–July 2023	85
Lake George / Uruwera Northeast	Chlorophyll-*a*	Apr 2012–July 2023	86
	Secchi disc	Jan 2015–July 2023	78
	Escherichia coli	Jan 2015–July 2023	81
	Nitrate nitrite	Apr 2012–July 2023	86
	Total nitrogen	Apr 2012–July 2023	55
	Dissolved reactive phosphorus	Apr 2012–July 2023	86
	Total phosphorus	Apr 2013–July 2023	86
	Turbidity (Lab FNU)	June 2018–July 2023	21
	Water temperature	Nov 2015–Apr 2023	347,809
	Ammoniacal nitrogen (adjusted)	Apr 2012–July 2023	86
Lake George / Uruwera Southwest	Chlorophyll-*a*	Apr 2012–July 2023	64
	Secchi disc	Jan 2015–July 2023	77
	Escherichia coli	Jan 2015–July 2023	77
	Nitrate nitrite	Apr 2012–July 2023	86
	Total nitrogen	Apr 2012–July 2023	51
	Dissolved reactive phosphorus	Apr 2012–July 2023	86
	Total phosphorus	Apr 2012–July 2023	82
	Turbidity (Lab FNU)	June 2018–July 2023	21
	Ammoniacal nitrogen (adjusted)	Apr 2012–July 2023	82
Lake Vincent Centre	Chlorophyll-*a*	Mar 2013–June 2023	83
	Secchi disc	Jan 2015–May 2023	75
	Escherichia coli	Jan 2016 –June 2023	74
	Nitrate nitrite	Mar 2013 –June 2023	82
	Total nitrogen	Mar 2013 –June 2023	50
	Dissolved reactive phosphorus	Mar 2013 –June 2023	83
	Total phosphorus	Mar 2013 –June 2023	83
	Turbidity (Lab FNU)	July 2018–June 2023	19
	Ammoniacal nitrogen (adjusted)	Mar 2013–June 2023	83

Site name	Attributes	Start date–End date	nMeas
Lake Vincent North	Chlorophyll-*a* Secchi disc *Escherichia coli* Nitrate nitrite Total nitrogen Dissolved reactive phosphorus Total phosphorus Turbidity (Lab FNU) Ammoniacal nitrogen (adjusted)	Mar 2013–June 2023 Jan 2015–May 2023 Jan 2016–June 2023 Mar 2013–June 2023 Mar 2013–June 2023 Mar 2013–June 2023 Mar 2013–June 2023 July 2018–June 2023 Mar 2013–June 2023	83 75 73 82 50 83 83 19 83
Lake Vincent Outflow 5 m downstream	Water temperature	May 2013–Mar 2017	97,594
Lake Vincent Tributary at Frasers Beach Road	Water level Water temperature	Dec 2018–Mar 2023 Dec 2018–Feb 2023	206,851 206,851
The Reservoir Centre	Chlorophyll-*a* Secchi disc *Escherichia coli* Nitrate nitrite Total nitrogen Dissolved reactive phosphorus Total phosphorus Turbidity (Lab FNU) Ammoniacal nitrogen (adjusted)	Mar 2013–June 2023 Jan 2015–June 2023 Jan 2016–June 2023 Mar 2013–June 2023 Mar 2013–June 2023 Mar 2013–June 2023 Mar 2013–June 2023 June 2018–June 2023 Mar 2013–June 2023	95 91 85 95 62 95 95 18 95
The Reservoir Monitoring Station	Dissolved oxygen Water temperature	Dec 2016–Feb 2019 Dec 2016–Feb 2019	66,939 66,941
The Reservoir Outflow 100 m downstream of The Reservoir	Water level Water temperature	Mar 2019–May 2023 Mar 2019–May 2023	253,173 253,842
The Reservoir Outflow at Haldane Bay	Water level Water temperature	Dec 2018–May 2021 May 2013–May 2021	149,495 330,172
The Reservoir Tributary at Haldane Curio Bay Road	Water level Water temperature	Dec 2018–May 2023 Dec 2018–May 2023	266,306 266,306
The Reservoir West	Chlorophyll-*a* Secchi disc *Escherichia coli* Nitrate nitrite Total nitrogen Dissolved reactive phosphorus Total phosphorus Turbidity (Lab FNU) Ammoniacal nitrogen (adjusted)	Mar 2013–June 2023 Jan 2015 –June 2023 Jan 2016 –June 2023 Mar 2013–June 2023 Mar 201–June 2023 Mar 2013–June 2023 Mar 2013–June 2023 Jun 2018–June 2023 Mar 2013–June 2023	95 90 85 95 62 95 95 18 95

4.2 State over time – trophic level index

The TLI was calculated for each of the three lakes at representative sites: Lake George / Uruwera Northeast, The Reservoir Centre and Lake Vincent Centre. To determine robust TLI calculations, the data were checked to ensure only measurements where all four of the TLI component variables (TN, TP, chlorophyll-*a* and Secchi depth) were measured on the same day. Any measurements for individual parameters that did not have corresponding measures for other variables were filtered from the dataset. We also use a minimum data abundance of quarterly samples within a single hydrological year to calculate the TLI. To allow insights into which components are influencing the TLI, we also plotted the average of the weighted sub-metrics.

The TLI fluctuates between years, but all are eutrophic, with values of 4.2 to 4.8 in Lake George / Uruwera, 4.3 to 4.6 in Lake Vincent and 4.6 to 4.9 in The Reservoir (black dots in Figures 4, 5 and 6). Lake George / Uruwera does not have adequate years with TLI calculated to infer any attributes from the key sub-metric parameters. In Lake Vincent Centre, TN is pulling the TLI upward in all years, although this influence is less strong in the last 2 years of data. In contrast, all of the TLI sub-metrics are similar in The Reservoir, with fluctuations in TLI being driven by relatively small changes in the chlorophyll-*a* sub-metric.

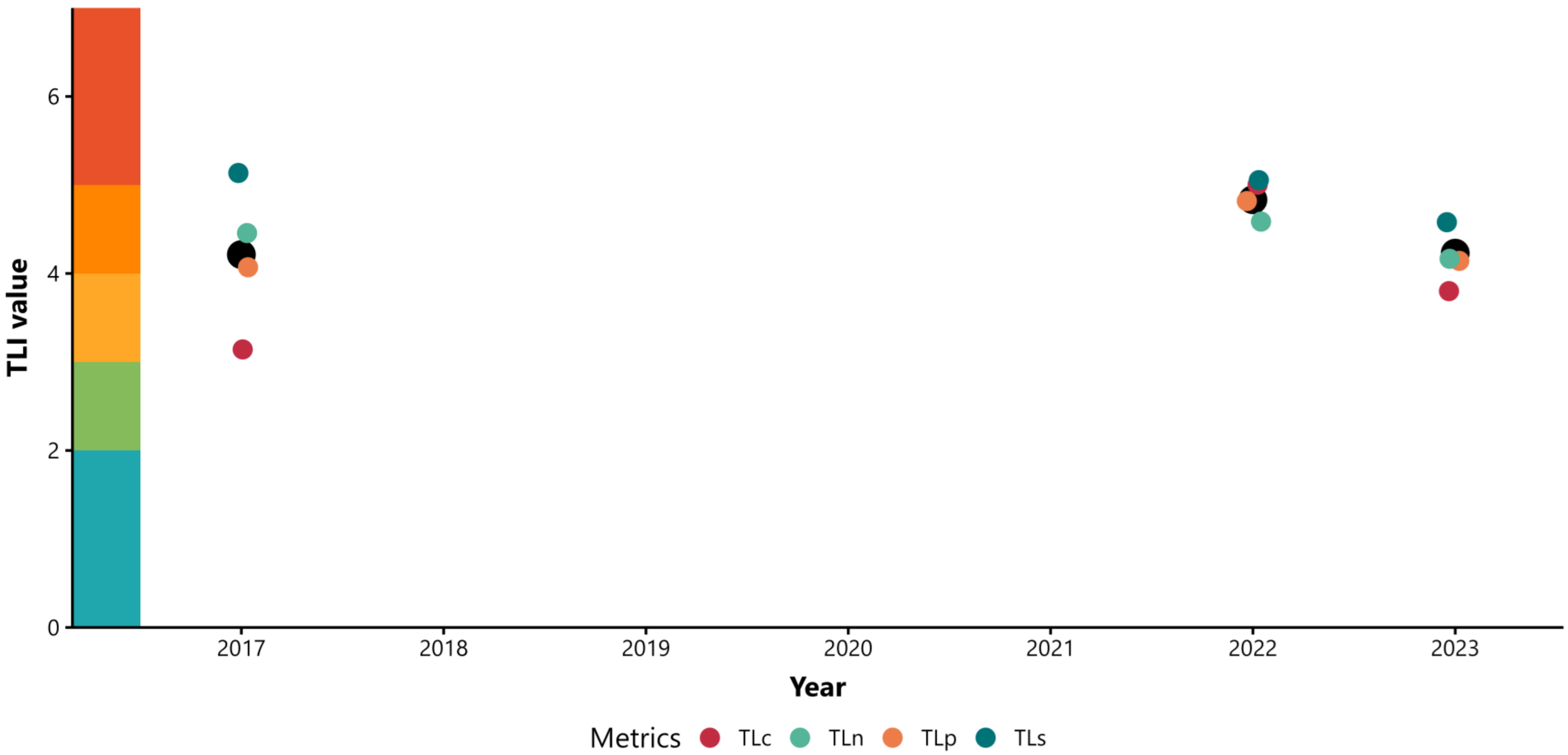


Figure 4. Trophic level index (TLI) results for Lake George / Uruwera Northeast (large black point) and sub-metric components for chlorophyll-*a* (TLc: red point), nitrogen (TLn: green point), phosphorus (TLp: orange point) and Secchi depth (TLs: blue point) for hydrologic years with data representation at least quarterly. The coloured bar on the left represents trophic state categories from microtrophic (blue) to supertrophic (red).

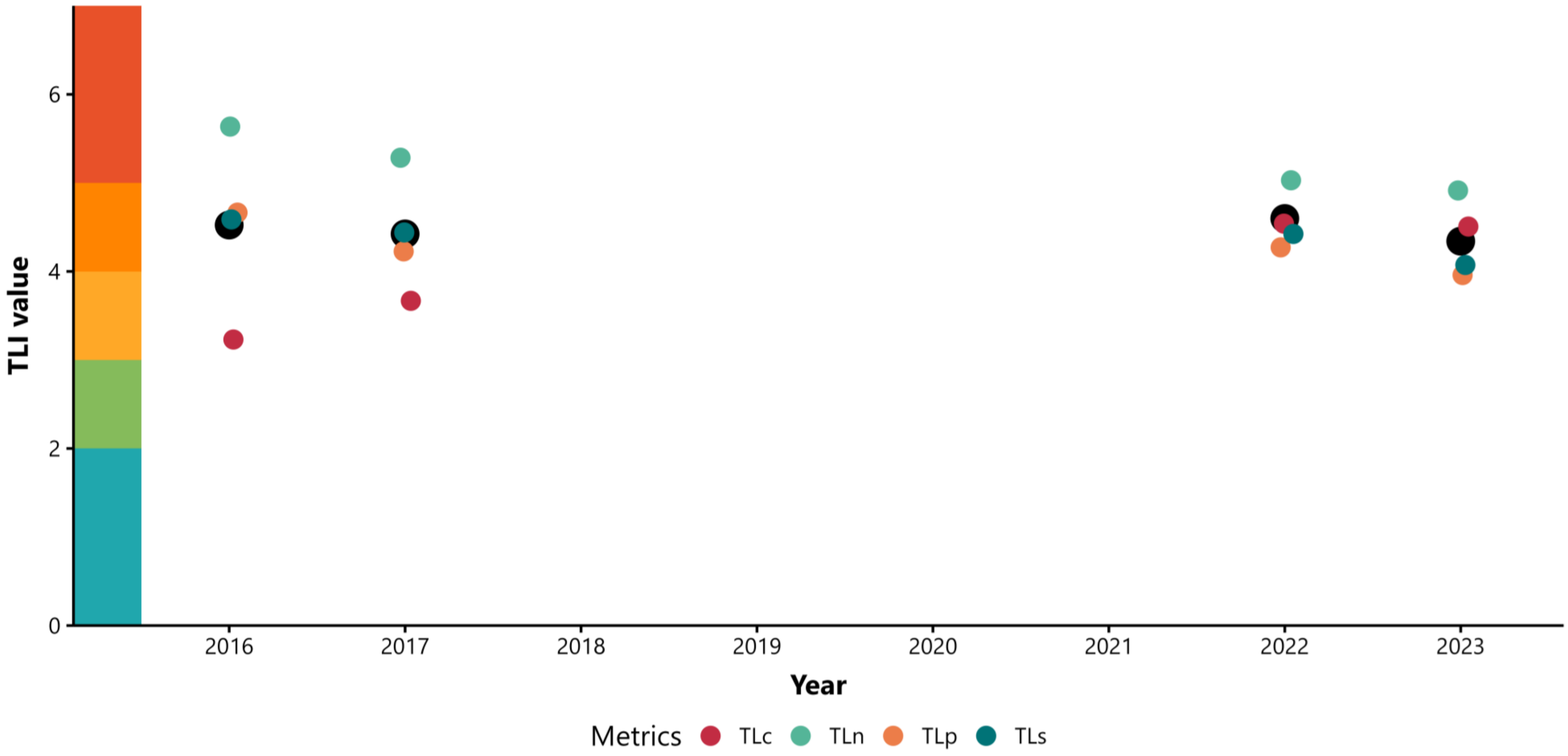


Figure 5. Trophic level index (TLI) results for Lake Vincent Centre (large black point) and sub-metric components for chlorophyll-*a* (TLc: red point), nitrogen (TLn: green point), phosphorus (TLp: orange point) and Secchi depth (TLs: blue point) for hydrologic years with data representation at least quarterly. The coloured bar on the left represents trophic state categories from microtrophic (blue) to supertrophic (red).

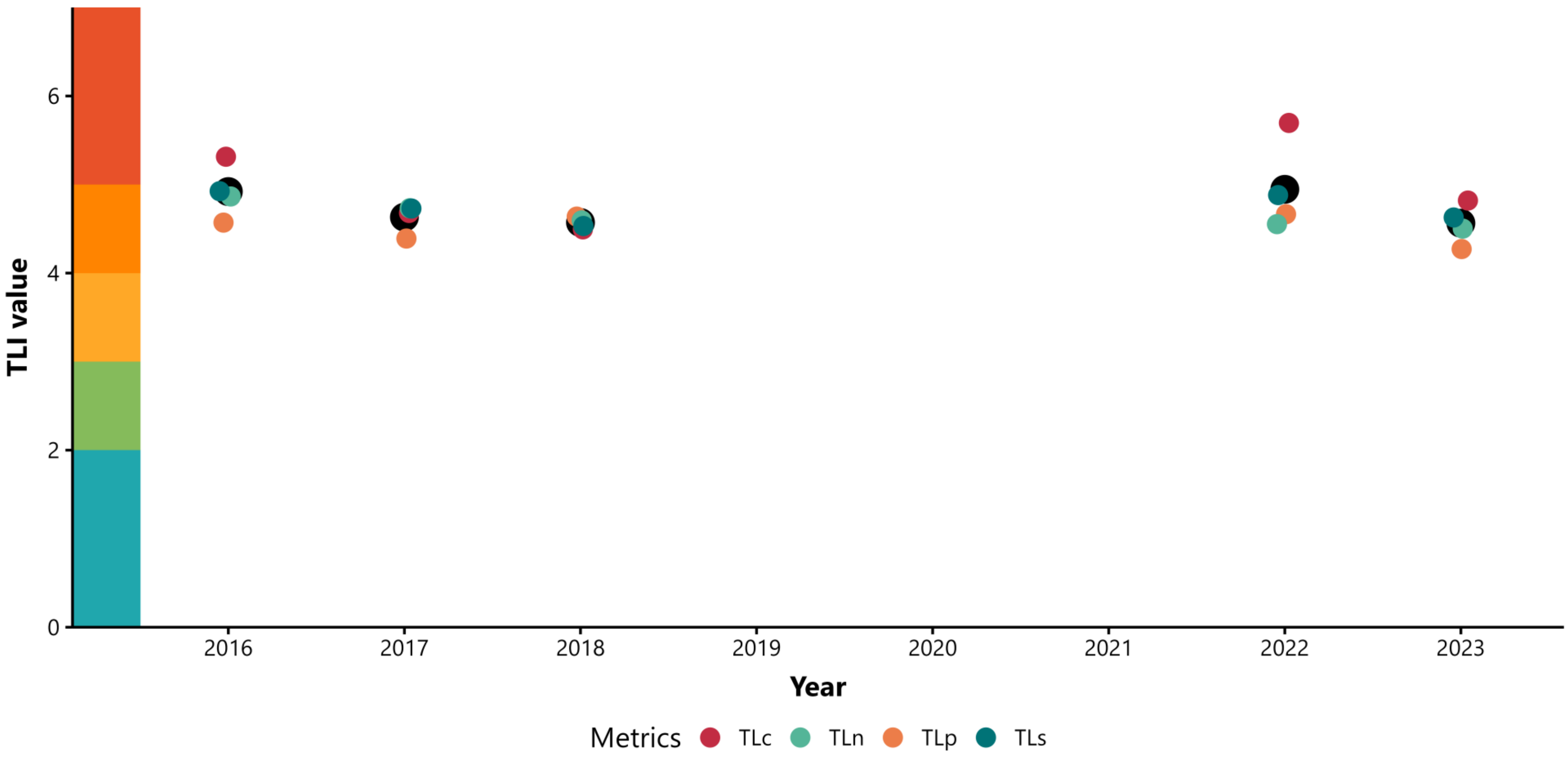


Figure 6. Trophic level index (TLI) results for The Reservoir Centre (large black point) and sub-metric components for chlorophyll-*a* (TLc: red point), nitrogen (TLn: green point), phosphorus (TLp: orange point) and Secchi depth (TLs: blue point) for hydrologic years with data representation at least quarterly. The coloured bar on the left represents trophic state categories from microtrophic (blue) to supertrophic (red).

4.3 Trends in lake attributes over time

Data were analysed using the trend assessment methodology provided by LandWaterPeople (LWP 2021). To undertake trend analyses, the data were first assigned their hydrological year (July to June) and checked for data frequency. Censored values (i.e. less or greater than laboratory detection analyses, denoted by < and > symbols) were identified with a flag for the analyses. The analyses were undertaken using the same methods as LAWA.[1] Initial indications suggested that trends could not be calculated for any of the Lake-Variable combinations, as the minimum data abundance requirements were not met. For trend calculations, a minimum of 90% of data points from monthly data must be present and all years must be represented. There is a fallback to enable quarterly sampling frequency, and this requires a minimum of 90% of the quarterly sampling data points to be present and all years to be represented. None of the data provided met the data abundance requirements to calculate trends over the entire monitoring period.

Monitoring frequency and consistency has increased over the last 5 years across the sites, thus we investigated whether trends could be calculated based on only the last 5 years of data. There was sufficient data for monthly monitoring of some variables to calculate trends over the last 5 years (2019 to 2023) for Lake George / Uruwera (Table 3). However, both Lake Vincent and The Reservoir still had insufficient data to calculate trends over the last 5 years. Plots for key water quality parameters for Lake Vincent and The Reservoir are provided in Appendix 1.

Table 3. Trend results for the attributes at Lake George / Uruwera over the 5 years from 2019 to 2023. The trend results categories range from 'very likely improving' to 'very likely degrading', using the LWP (2021) trend analysis methodology.

Site name	Attribute	Trend result
Lake George / Uruwera – Northeast	Total nitrogen	Very likely degrading
	Total phosphorus	Very likely degrading
	Secchi disc	Very likely degrading
	Chlorophyll-*a*	Likely degrading
	Escherichia coli	Indeterminate
	Nitrate-nitrite nitrogen	Likely improving
	Ammoniacal nitrogen (Adjusted)	Likely improving
	Dissolved reactive phosphorus	Very likely improving
Lake George / Uruwera – Southwest	Total phosphorus	Very likely degrading
	Secchi disc	Very likely degrading
	Escherichia coli	Very likely degrading
	Total nitrogen	Likely degrading
	Chlorophyll-*a*	Likely degrading
	Ammoniacal nitrogen (Adjusted)	Indeterminate
	Nitrate-nitrite nitrogen	Likely improving
	Dissolved Reactive Phosphorus	Very likely improving

[1] See factsheet: https://www.lawa.org.nz/learn/factsheets/calculating-water-quality-trends-in-rivers-and-lakes

In-lake sites for Lake George / Uruwera had very likely improving trends for dissolved reactive phosphorus. This positive trend is likely to be offset by an increase in TP, which had a very likely degrading trend for both sites. Likewise, although there are indeterminate or likely improving trends for some of the nitrogen species (ammoniacal and nitrate/nitrite), the TN was likely or very likely degrading. Visual clarity is very likely degrading at both sites, and the chlorophyll-*a* is also worsening. Trend results should be interpreted with some caution, as they inform about the direction of a trend but not the magnitude. A site with a very likely degrading trend might be experiencing a very small decline, which is nonetheless statistically identified through the analysis.

The Secchi disc depth, chlorophyll-*a*, *E. coli,* TN and TP data for the Northeast site in Lake George / Uruwera over the study period is plotted in Figure 7 to Figure 12.

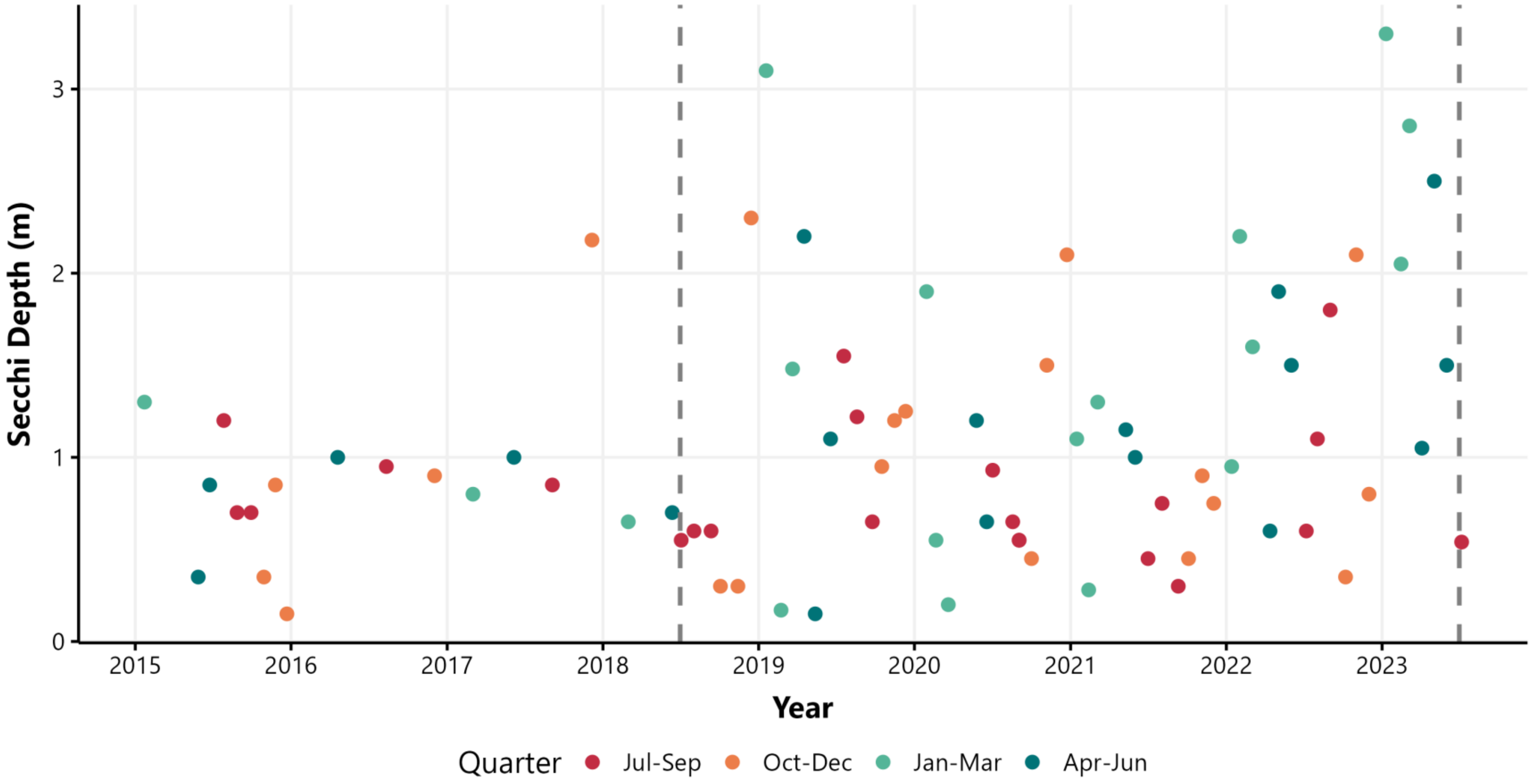


Figure 7. Lake George / Uruwera – Northeast site. Secchi disc depth (visual clarity) across the dataset. The space between the vertical grey lines represents the 5 years used for trend analyses.

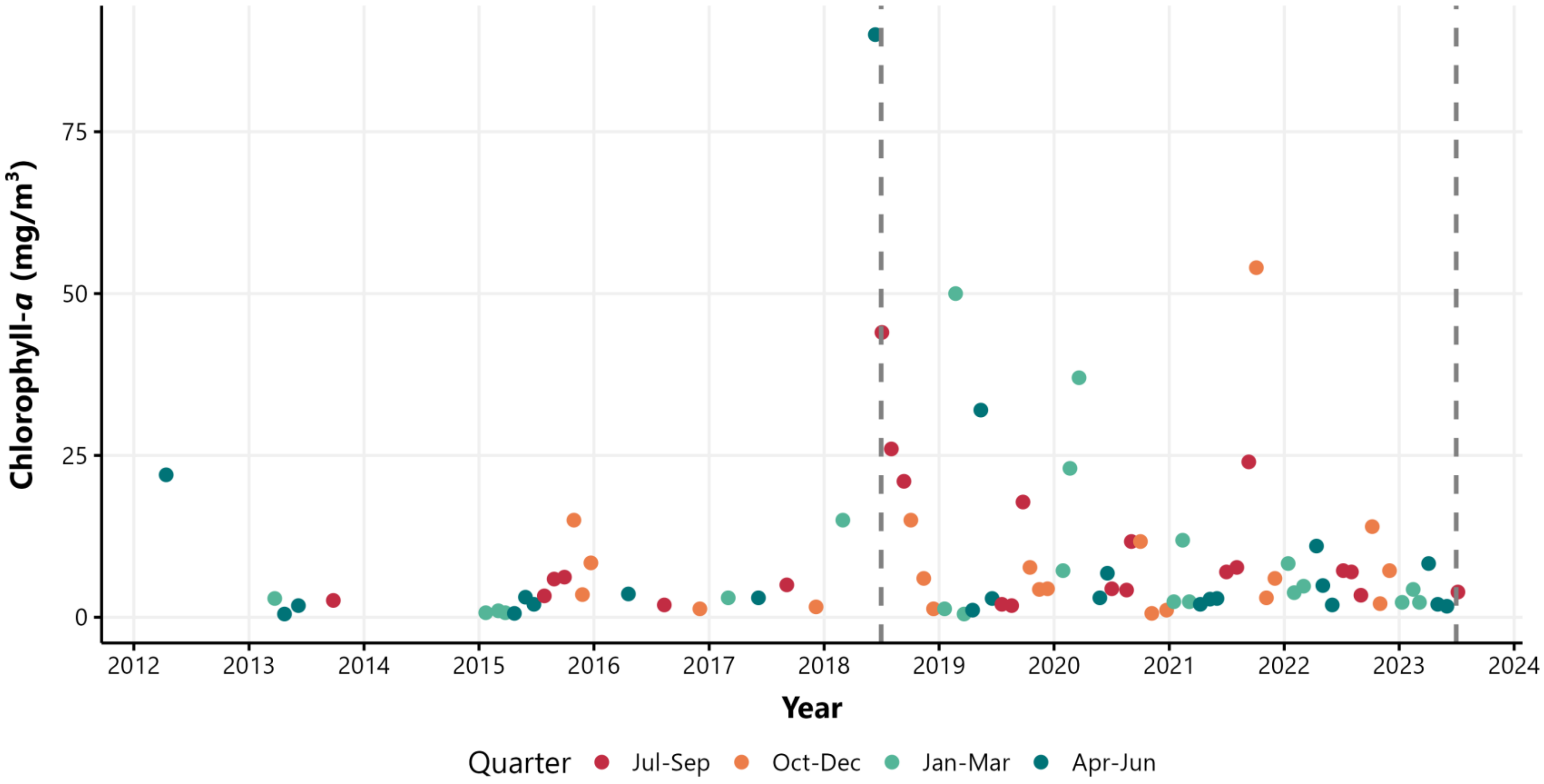


Figure 8. Lake George / Uruwera – Northeast site. Chlorophyll-*a* concentrations over the monitored period. The space between the vertical grey lines represents the 5 years used for trend analyses.

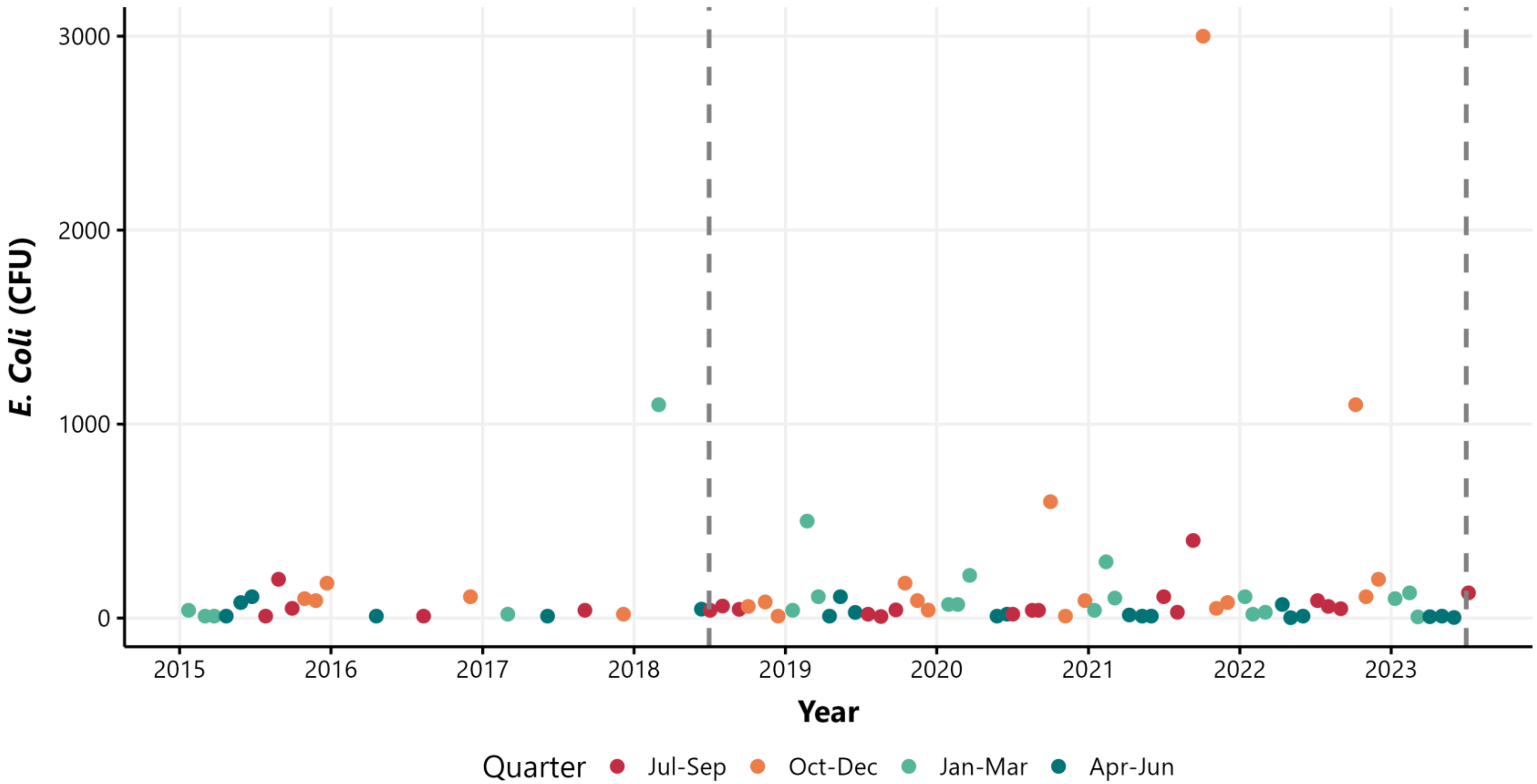


Figure 9. Lake George / Uruwera – Northeast site. *E. coli* concentrations over the monitored period. The space between the vertical grey lines represents the 5 years used for trend analyses.

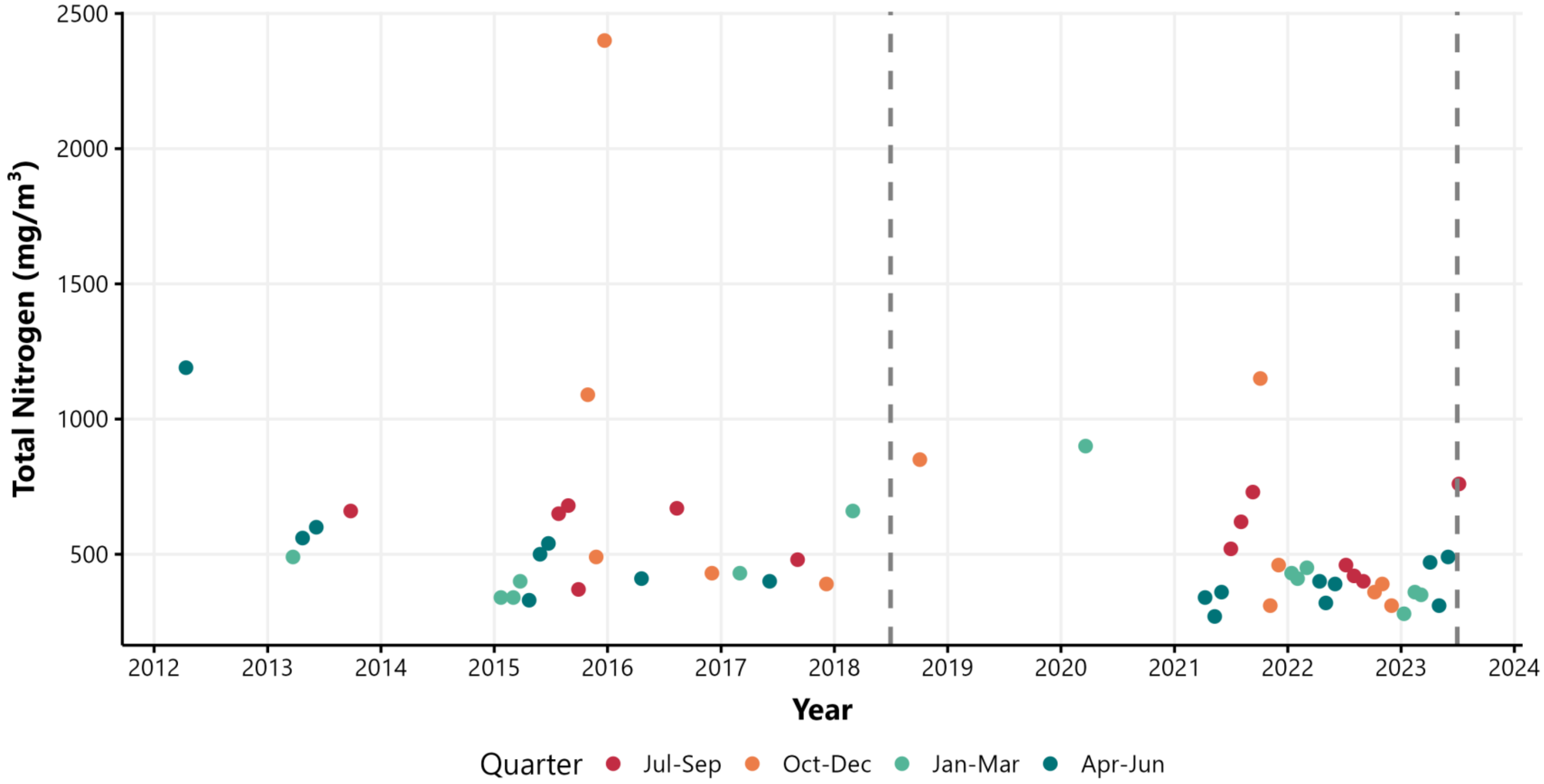


Figure 10. Lake George / Uruwera – Northeast site. Total nitrogen over the monitored period. The space between the vertical grey lines represents the 5 years used for trend analyses.

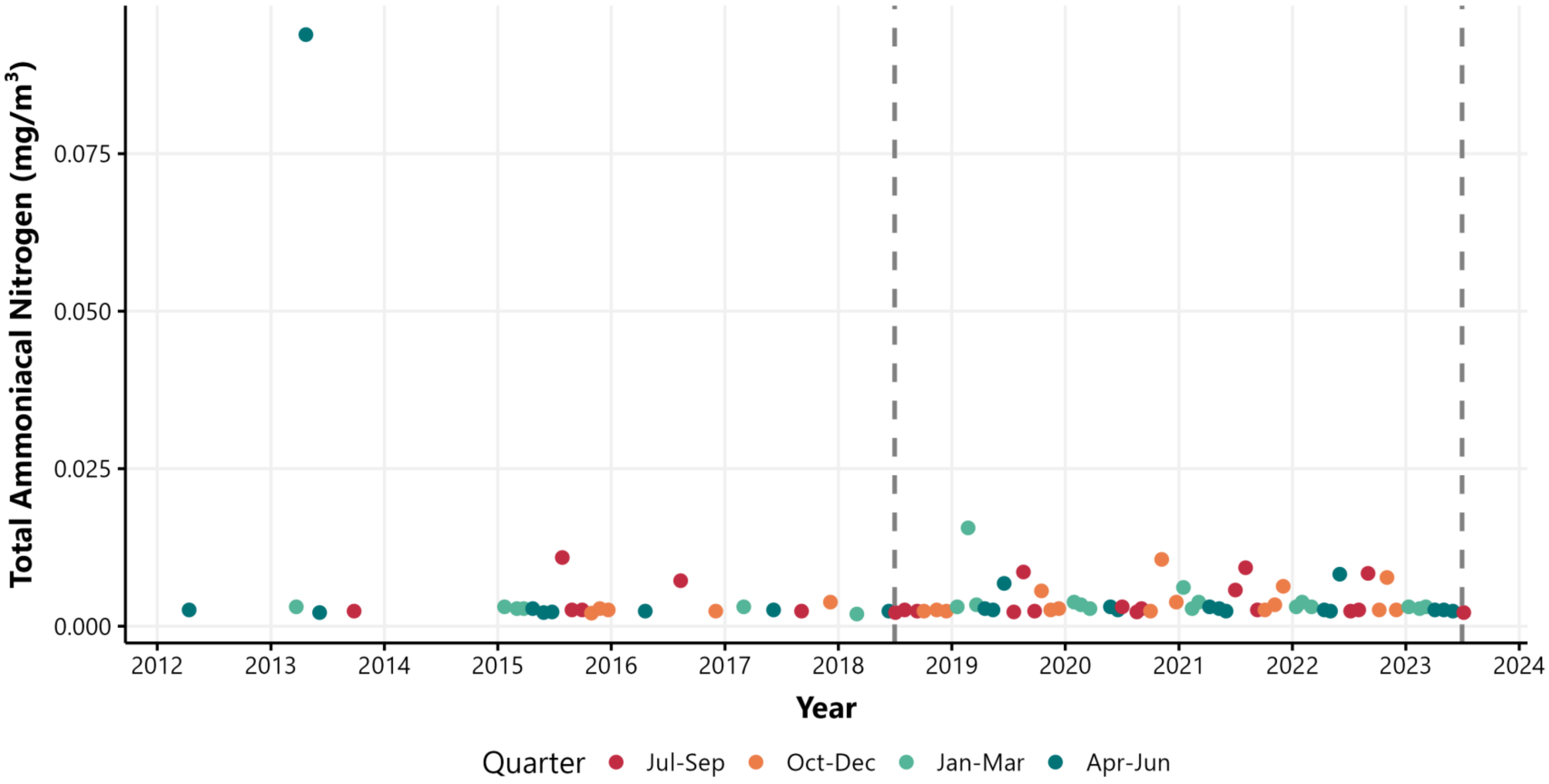


Figure 11. Lake George / Uruwera – Northeast site. Ammoniacal nitrogen (pH adjusted) over the monitored period. The space between the vertical grey lines represents the 5 years used for trend analyses.

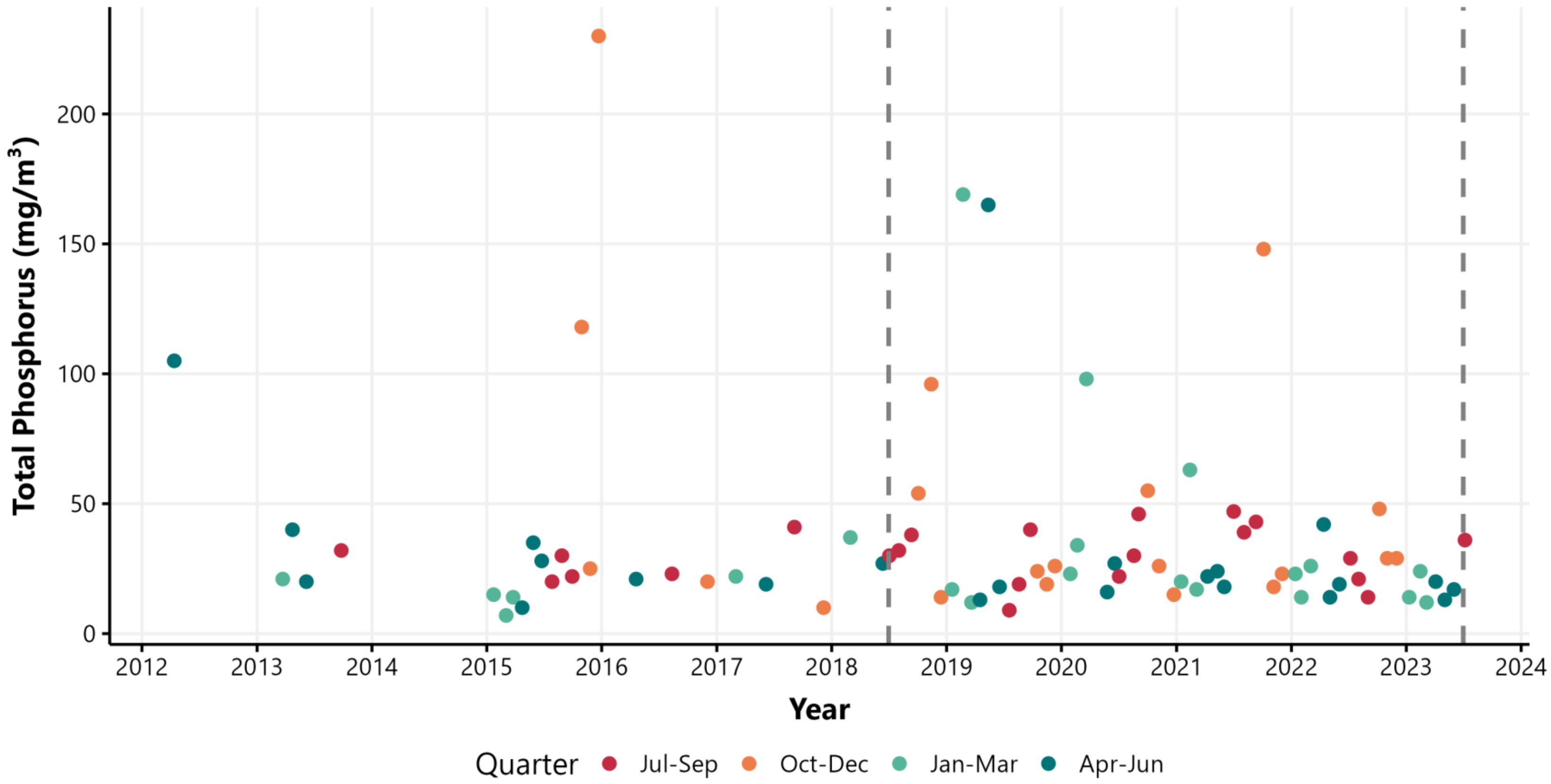


Figure 12. Lake George / Uruwera – Northeast site. Total phosphorus concentrations over the monitored period. The space between the vertical grey lines represents the 5 years used for trend analyses.

4.4 Cyanobacteria

The cyanobacterial dataset consisted of cell densities (cells per mL or units per mL) of taxa identified to various taxonomic resolutions. Some were identified to order only, while there were also genus and species-level taxonomic results. The data were aggregated at the genus level and grouped by lake and hydrologic year. The three most abundant taxa in each hydrologic year were identified for each of the lakes.

In Lake George / Uruwera, picocyanobacteria (not otherwise specified to a genus) was the dominant taxonomic group in 5 of the 7 years that data were available (Figure 13). *Aphanocapsa*, *Aphanothece* and *Chroococcus* were all in the top three dominant taxa from 2018 to 2020 but have not appeared in the dominant taxa since that period.

The cyanobacterial cell counts were much lower in Lake Vincent compared to Lake George / Uruwera, and the community composition was more variable (Figure 14). Filamentous cyanobacterial taxa made up a larger part of the community in Lake Vincent, with *Phormidium*, *Oscillatoria* and *Planktothrix* all present.

The Reservoir had a range of cyanobacteria present, with both picocyanobacteria (not otherwise specified to a genus) and *Limnococcus* commonly in the dominant taxa over time (Figure 15).

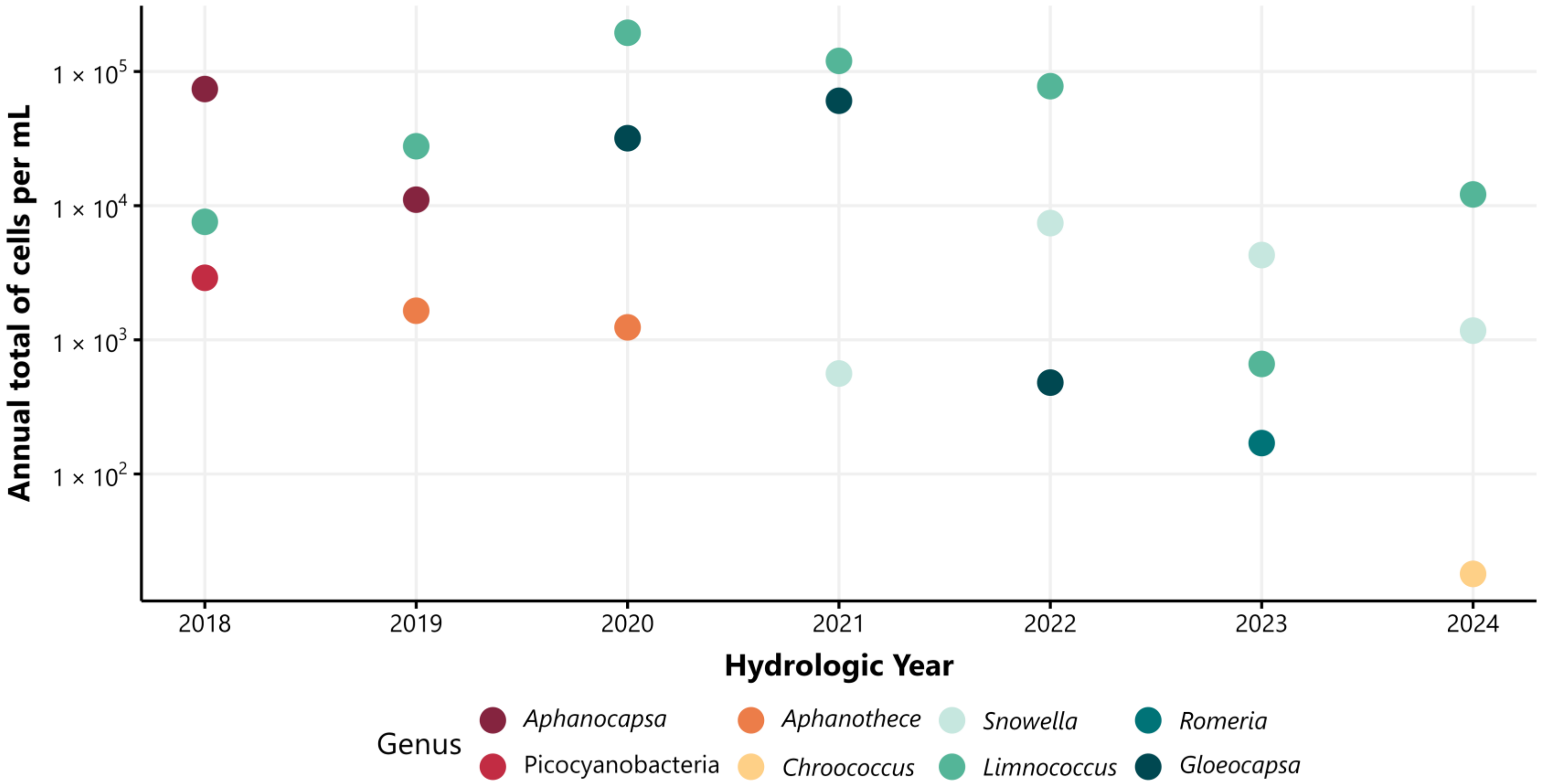


Figure 13. The three most dominant cyanobacterial taxa (aggregated at genus level) in each hydrological year plotted over time in Lake George / Uruwera. Note that the y-axis scale is log-transformed for clarity, and the taxon colours are specific to this plot.

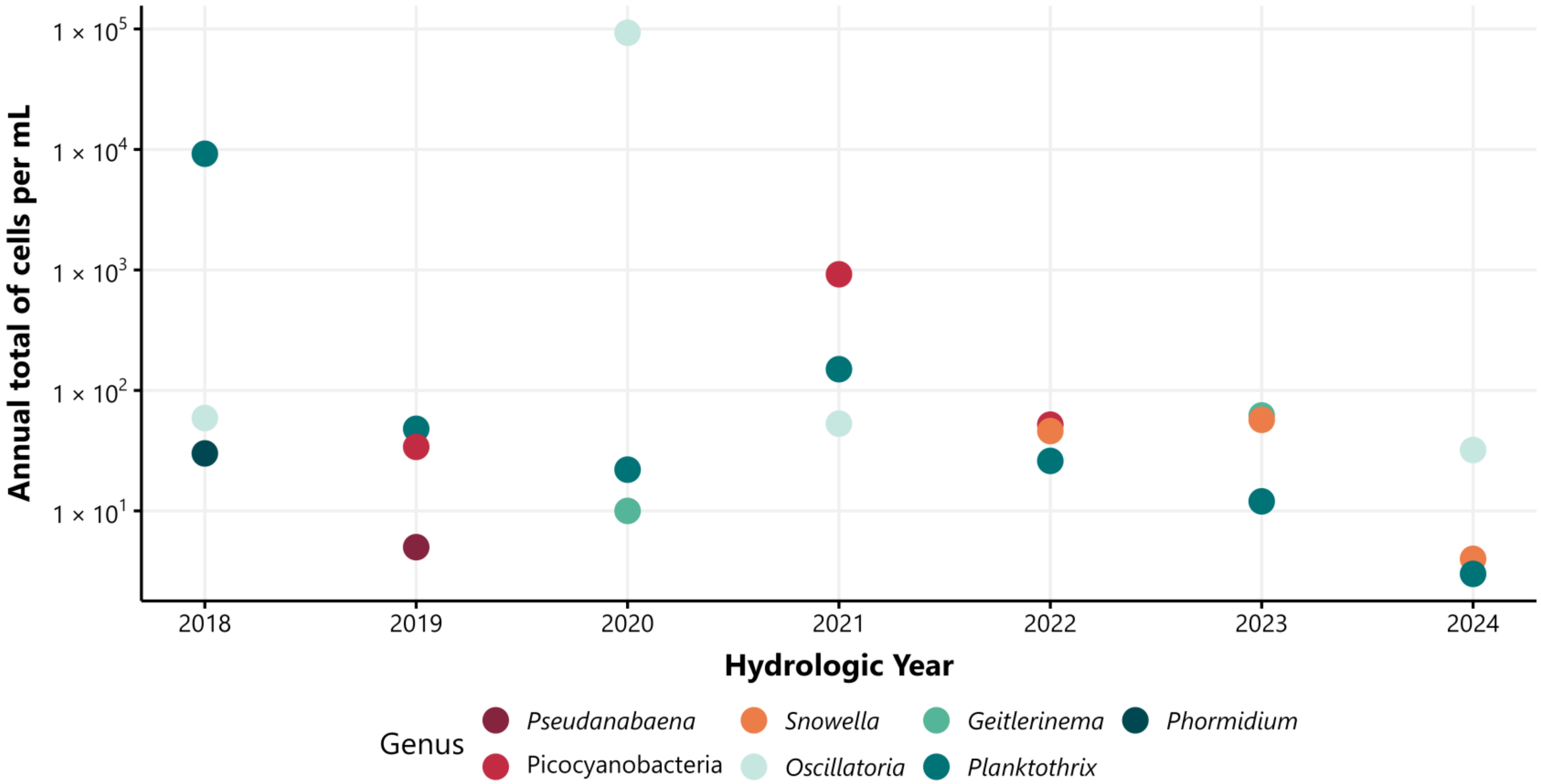


Figure 14. Dominant cyanobacterial taxa (aggregated at genus level) in each hydrological year plotted over time in Lake Vincent. Note that the y-axis scale is log-transformed for clarity, and the taxon colours are specific to this plot.

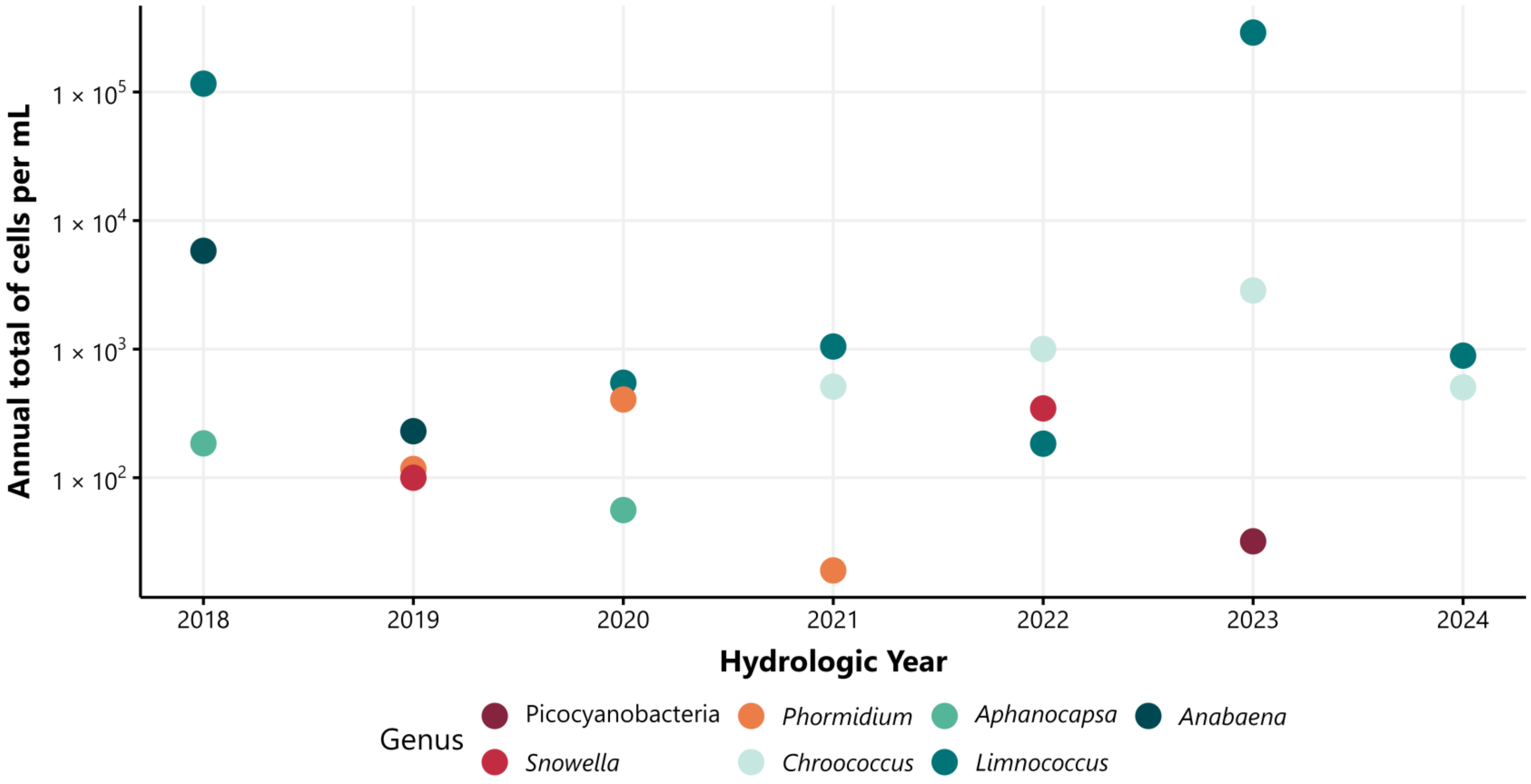


Figure 15. Dominant cyanobacterial taxa (aggregated at genus level) in each hydrological year plotted over time in The Reservoir. Note that the y-axis scale is log-transformed for clarity, and the taxon colours are specific to this plot.

5. Data and results from the Lakes380 programme

5.1 Introduction

Lakes George / Uruwera and Vincent were sampled as part of the national Our lakes' health: past, present, future programme, also known as Lakes380. As part of this programme, water, surface sediment and sediment core samples were collected in January 2019. The water and surface sediment samples were analysed for nutrients, trace metals and bacterial environmental DNA (eDNA; data not presented). The sediment cores were analysed using various techniques to explore if, how and why the lakes have changed over time. Due to budget and time constraints, only the sediment core from Lake Vincent was analysed.

5.2 Methods

Water and surface sediment nutrient and metal analysis

Surface water (1 L) for chlorophyll-*a* was collected and kept on ice until further processing. A sub-sample (up to 600 mL) was filtered (GF/C, Whatman, UK) and the volume was recorded. Filters were placed in aluminium foil and stored in the dark (-20 °C). Chlorophyll-*a* analysis was undertaken following the APHA 10200 H method at Watercare Laboratories (Auckland, New Zealand) with a reporting limit of 0.0006 mg/L.

Water samples (1 L) were collected using an integrated tube sampler through the surface mixed layer. Sub-samples were taken for TN, TP and total organic carbon (TOC). Analyses of total nutrients were undertaken using APHA 4500 methods on a flow injection analyser. Reporting limits for TN and TP were 0.1 g/m^3 and 0.005 g/m^3, respectively. Analyses of TOC were undertaken by combustion analysis at 850 °C using APHA 5310 B methods with reporting limits of 0.5 g/m^3. A further sub-set of samples was filtered (0.45 µm) and analysed by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS), based on the US Environmental Protection Agency (EPA) method 200.8 for cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), nickel (Ni) and zinc (Zn). Reporting limits (mg/kg) were 0.00001, 0.0002, 0.0002, 00005, 0002 and 0.001, respectively.

Samples for surface sediment nutrient and elemental analyses were collected by Uwitech gravity corer (90 mm diameter core). Five cores were taken, and the top 2 cm of sediment were removed using a core cutter and combined in a 500 mL container. These were stored chilled (4 °C) and shipped to the laboratory within 48 hours for nutrient and elemental characterisation.

Surface sediment was homogenised and centrifuged (3,000× g, 40 mins, 4 °C), and the pore water was decanted. The sediments were analysed for metals using the methods described by Pearman et al. (2020). Briefly, the sediment was dried, passed through a 2 mm sieve and analysed using acid digestion followed by ICP-MS, based on the US EPA method 200.8, for the following metals: iron (Fe), manganese (Mn), aluminium (Al), calcium (Ca), Pb, Cu, Zn, Cd, phosphorus (P) and sulphur (S). Reporting limits (mg/kg) were 12.5, 0.125, 2.5, 12.5, 0.05, 0.075, 0.05, 0.005, 10 and 250, respectively. Total nitrogen and TOC were analysed using catalytic combustion (at 900 °C, O_2) and separated using a thermal conductivity detector (reporting limit for both g/100 g). Oven drying of a known sediment volume was used to calculate bulk density, while oven drying followed by ashing (550 °C and 950 °C) and gravimetric determination were used to measure organic matter and carbonate content. Values were compared with the median values obtained from about 200 lakes analysed nationally as part of the Lakes380 programme.

To determine the forms of phosphorus bound in the sediment, chemical sequential extraction was undertaken on thawed sediment samples following a 'Psenner' type scheme modified by Rydin (2000) and Waters et al. (2021). In this sequential extraction scheme, sediments are shaken in a series of chemical reagents. The analysis provided the following phosphorus fractions:

- *Exchangeable phosphorus (Ex-P)*: very loosely bound and soluble phosphorus.
- *Redox-sensitive phosphorus (Red-P)*: phosphorus that may be mobilised by low dissolved oxygen in the surrounding water column. Commonly associated with reducible mineral phases such as Fe and Mn (hydr)oxides.
- *pH-sensitive phosphorus (pH-P)*: phosphorus that can be mobilised by high pH in the surrounding water column. Commonly bound to the surfaces of mineral phases such as Al (hydr)oxides as well as the less reactive Fe and Mn (hydr)oxides, clays and organic particulates.
- *Organic phosphorus (Org-P)*: easily degradable organic fraction.
- *Calcium-associated phosphorus (Ca-P)*: the phosphorus fraction associated with Ca minerals, including apatite and carbonates as well as refractory metal oxides. This fraction is not considered to be bioavailable.
- *Residual phosphorus (Res-P)*: consists of largely refractory organic material. This fraction is not considered to be bioavailable.
- *Total phosphorus (TP)*: determined by the sum of all fractions.

The Ex-P, Red-P and Org-P constitute the more mobile phosphorus fractions (Waters 2021) and are most likely to be, or become, bioavailable. The sum of these fractions is referred to as 'potentially mobile P'. Values were compared with the median values obtained from 176 lakes analysed nationally as part of the Lakes380 programme and 28 shallow dune lakes from the same dataset.

Sediment core collection and analysis (Lake Vincent only)

Four sediment cores were obtained near the deepest part of Lake Vincent using a Uwitech gravity corer equipped with 2 m long, 90 mm diameter polyvinyl chloride barrels. The barrels underwent cleaning with 2% sodium hypochlorite (bleach) before coring. Once retrieved, the cores were sealed and stored in darkness at 4 °C for about 4 weeks before sub-sampling was conducted.

The cores were longitudinally split using a Geotek core splitter and guillotine. To prevent cross-contamination from the splitting process, the top 2–3 mm of one half-core per lake was carefully removed using a sterile spatula. Sub-samples of approximately 0.5 g were extracted from the centre of the half-core at various depths using a sterile spatula. One portion of the core was sub-sampled for pollen and DNA analyses, while the other half was used for hyperspectral scanning.

Pollen

Pollen was obtained from 0.25 cm^3 of sediment by treating it with 10% hot hydrochloric acid, acetolysis and 6-micron sieving. Exotic Lycopodium tablets were included in each sample to enable pollen concentrations to be determined. Identification of pollen and spores was carried out using standard references and the Aotearoa New Zealand reference collection.

Data are presented as the relative frequency of a minimum pollen sum of 150 grains. This sum includes pollen from all dryland plants: trees, shrubs and herbaceous plants, and non-native plant taxa. Bracken fern, *Pteridium esculentum*, is included in the dryland pollen sum because in a post-disturbance landscape, its functional morphology is closer to a shrub than a fern, and a stand is ecologically equivalent to shrubland (McGlone et al. 2005). Pollen of other groups (wetland, aquatics, ferns, tree ferns and non-palynomorphs) were excluded from the sum, but their percentages were calculated as a proportion of dryland pollen, plus the respective group.

Chronology

An age model was developed for the Lake Vincent core. Four terrestrial leaf macrofossils were extracted by picking *in situ* material from the split core surface. Macrofossils were cleaned and pre-treated using an acid–alkali–acid procedure to remove carbonates, fulvic and humic compounds. The pre-treated macrofossils were converted to CO_2 by combustion, graphitised and measured by accelerator mass spectrometry following Baisden et al. (2013). Conventional radiocarbon ages were converted to calendar years using the ShCaL20 calibration curve (Hogg et al. 2020), while those that returned modern ages were calibrated using the BHDCGO curve (Turnbull et al. 2017). A Bayesian framework was used to conduct age-depth modelling using OXCAL 4.4 (Ramsey 2009). Briefly, pollen and charcoal biostratigraphy and calibrated ^{14}Carbon dates were used in a P_Sequence prior model (with a variable event thickness constant k) to generate probability density functions that were integrated with core depth (Ramsey 2008; Ramsey and Lee 2013) to produce an age model and estimates of age uncertainty.

Pollen data were used to delineate human occupation periods in the sediment downcore data. An increase in bracken fern (*Pteridium esculentum*) is used across Aotearoa New Zealand as a chronological marker for the first presence of Māori activity and settlement, as it is both an indicator of landscape disturbance (i.e. it is one of the first successional species after vegetation clearance) and a nutritional source (McGlone and Wilmshurst 1999; McWethy et al. 2010; Newnham et al. 2018). In this report, the period before the increase in bracken fern is called the pre-human phase, and the period following is referred to as post-Māori settlement. Pine (*Pinus* spp.) and other non-native taxa were introduced by European colonialists and are used to mark European activity in a landscape; this period is referred to as post-European settlement. In the graphs, the phases are indicated by lines that cross the first samples, with pollen indicative of the different human occupation phases.

The core was scanned using a hyperspectral core scanner equipped with a Specim sCMOS-CL-50-V10E-SCB camera working in the visual to near-infrared range (400 nm to 1000 nm). Measurements were captured with a spectral resolution of 1.3 nm and a spatial resolution of 41 µm. This study analysed spectral data using RABD660/670, which is correlated with the sedimentary pigment chlorophyll-*a* and its degradation products.

Environmental DNA (eDNA)
DNA was extracted from approximately 0.25 g of sediment per sample using the PowerSoil kit (Qiagen), and the V3–V4 region of the bacterial 16S rRNA gene was amplified by polymerase chain reaction. The data were processed as detailed in Pearman et al. (2020). Principal coordinates analysis (PCA) ordinations were undertaken based on Bray–Curtis distance matrices to assess bacterial community change over time.

Currently, it is challenging to make ecological inferences about changes in the sediment core bacterial communities, as the ecology of most species remains largely unknown. As a first step to draw some ecological information from the sediment core data, the data were converted to inferred functions. The functional profiles of the bacterial communities were inferred from the 16S rRNA composition using the software Paprica (Bowman and Ducklow 2015). This places the 16S rRNA gene sequences into a phylogenetic tree containing bacteria with sequenced genomes. The probable metabolism was then predicted based on the functional capability of the nearest sequenced genomes in the phylogenetic tree. Genes encoding enzymes related to denitrification, dissimilatory nitrate reduction to ammonia, and sulphate reduction were sub-set for analysis.

Analysis of these genes allows us to explore changes in:

- Denitrification – the process that converts nitrate to nitrogen gas. An increase in the presence of bacteria able to perform this function could suggest an increase in nitrates in the waterbody.
- Nitrate reduction – the process that converts nitrate to nitrite. This is generally an anaerobic process. An increase in this profile could be indicative of increased nitrates and lower oxygen levels.
- Sulphate reduction – sulphate reducers derive their energy from the anaerobic oxidation of organic compounds. An increase in this profile may be indicative of anoxia and / or low oxygen levels.

5.3 Results

Water and surface sediment metal and nutrients

The concentration of nutrients and metals in the surface waters of Lakes Vincent and George / Uruwera (collected in January 2019) was compared to the national average from the Lakes380 programme (Figure 16). Except for ammoniacal nitrogen, all other nutrients and metals were above the national medium in Lake George / Uruwera. Of note were the high levels of metals in Lake George / Uruwera. In Lake Vincent, chlorophyll-*a* was below the national median, but all other nutrients and metals were above or very close to the median. Except for iron and manganese in Lake Vincent, the nutrients and metals in the surface sediment of Lakes George / Uruwera and Vincent were below the national medians (Figure 17).

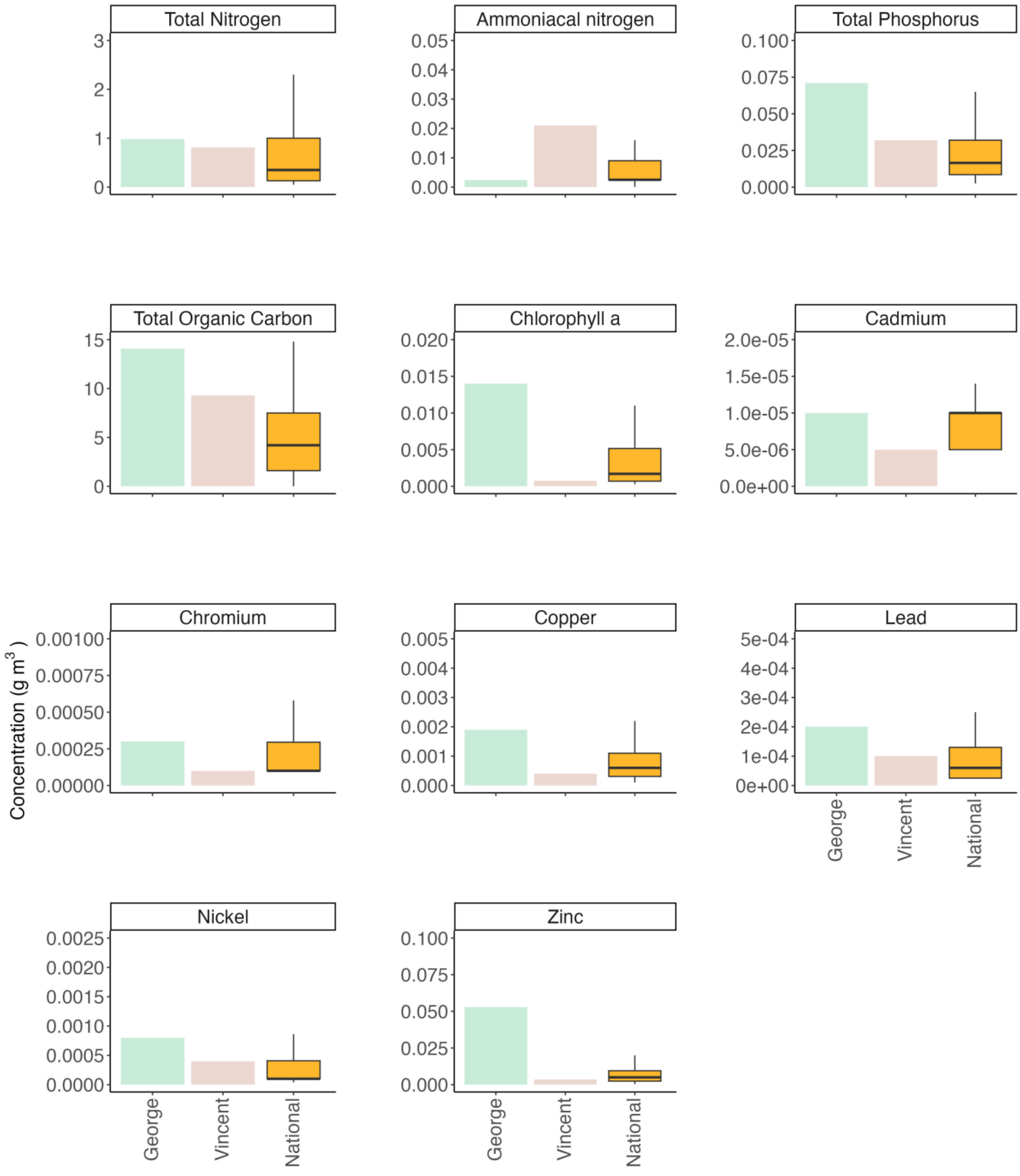


Figure 16. Nutrient and elemental concentrations in surface water samples collected from Lakes George / Uruwera and Vincent compared to data for a selection of lakes in Aotearoa New Zealand sampled as part of the Lakes380 programme (the total number of lakes in the national dataset varies between 239 and 287 depending on the variable measured). Black line shows median. Note that the y-axis scale varies.

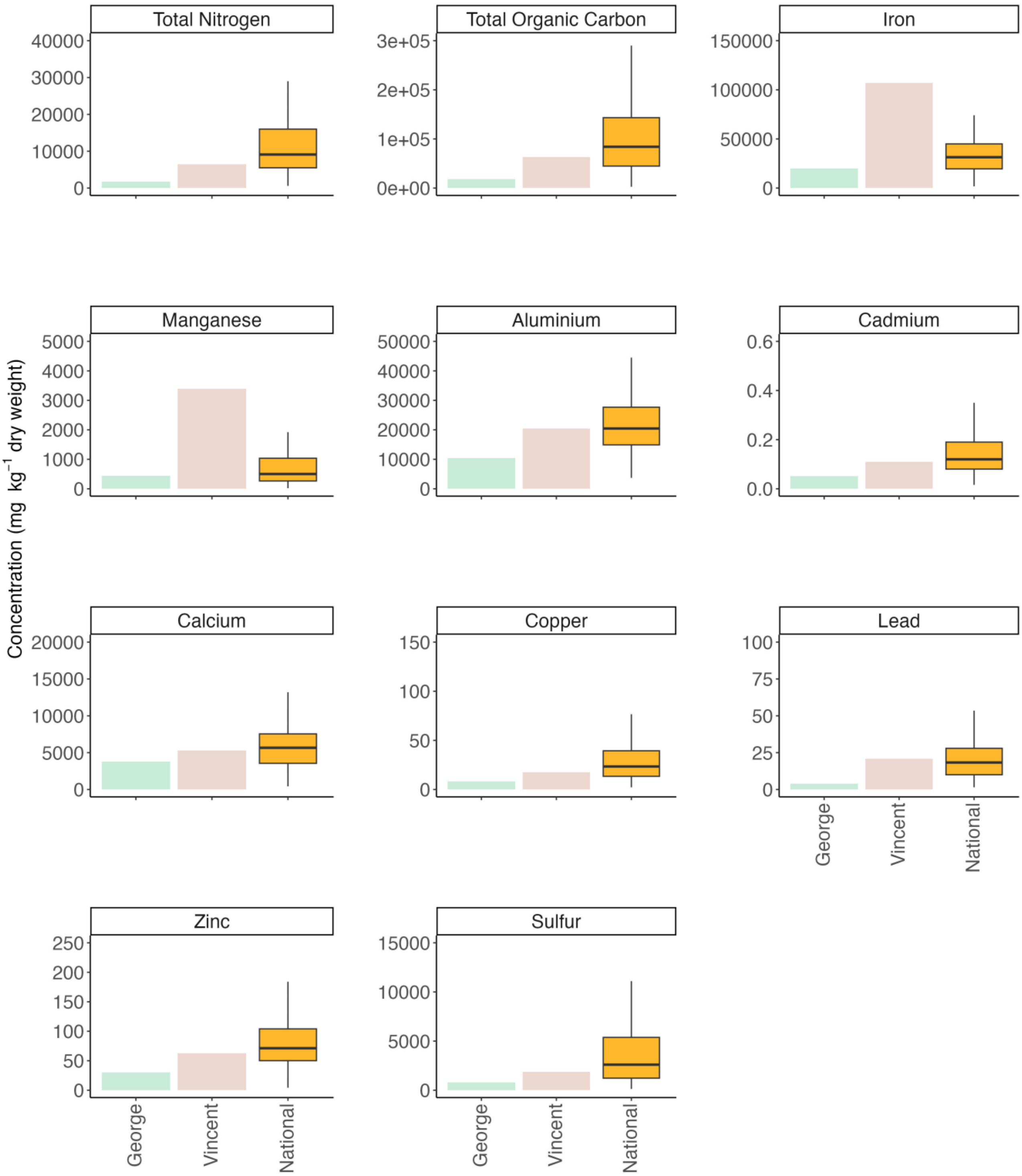


Figure 17. Sediment chemistry for samples from the top 0–2 cm of the lakebed sediments compared to data for a selection of lakes in Aotearoa New Zealand sampled as part of the Lakes380 programme (n = 214 lakes) from selected lakes in Aotearoa New Zealand. Black line shows median. Elemental results are total recoverable content. Note that the y-axis scale varies.

The TP content in Lake George / Uruwera (268 mg P kg^{-1} DW) was well below the national and shallow dune lake medians (1,568 mg P kg^{-1} DW and 1,807 mg P kg^{-1} DW; Figure 18). In contrast, the TP content in the Lake Vincent (2,485 mg P kg^{-1} DW) sediment was above the national medians.

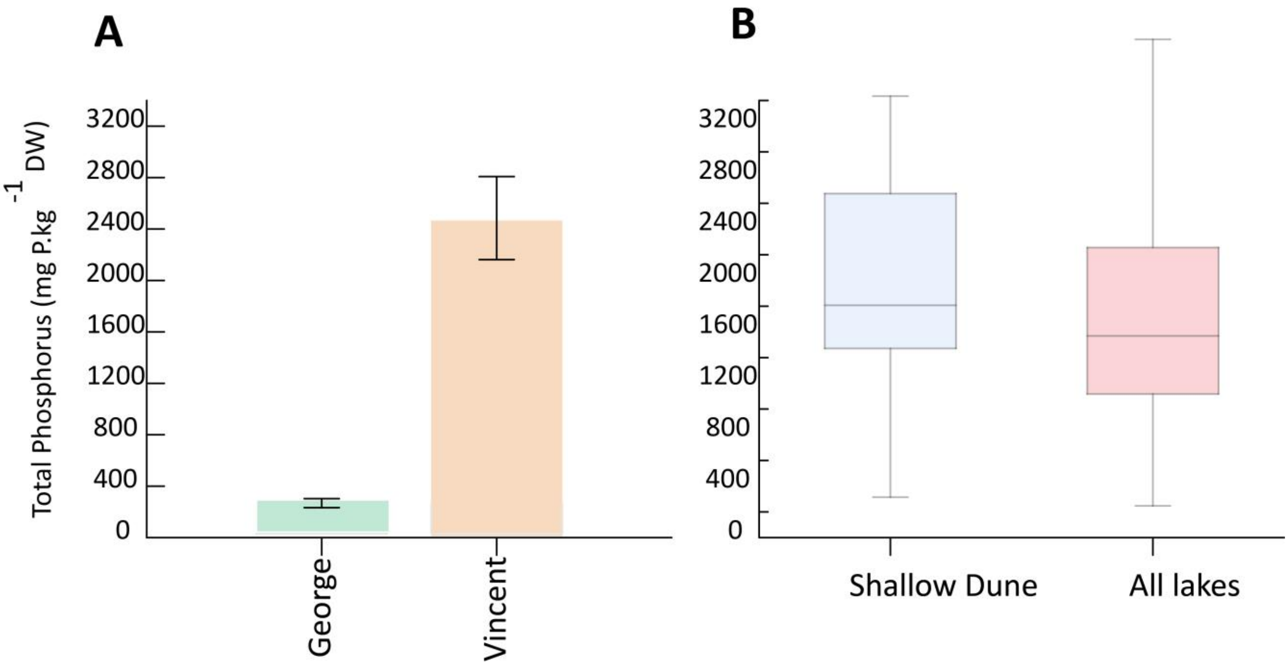


Figure 18. Total phosphorus in (A) Lakes George / Uruwera and Vincent surface sediment compared to (B) data for a selection of lakes in Aotearoa New Zealand sampled as part of the Lakes380 programme (n = 178 lakes) and the shallow dune lakes (n = 28 lakes) from the same dataset. The black line shows the median.

Potentially mobile phosphorus content in the sediments of Lake George (147 mg P kg^{-1} DW) were very low (Figure 19). In contrast, those in Lake Vincent (2,163 mg P kg^{-1} DW) were well above the national and shallow dune lake medians (Figure 19).

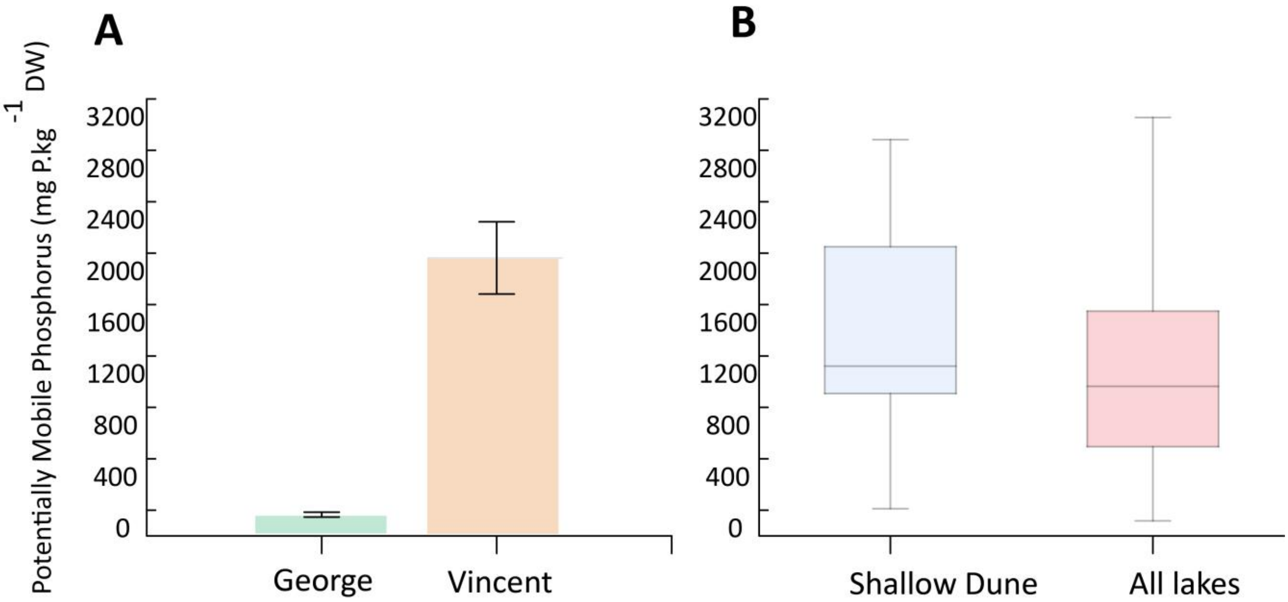


Figure 19. Potentially mobile phosphorus in (A) Lakes George / Uruwera and Vincent surface sediment compared to (B) data for a selection of lakes in Aotearoa New Zealand sampled as part of the Lakes380 programme (n = 178 lakes) and shallow dune lakes (n = 28 lakes) from the same dataset. The black line shows the median.

Sediment core results

The pollen and charcoal results indicated that before human arrival, Lake Vincent was surrounded by native forest dominated by rimu, with a sub-canopy abundant in tree ferns (Figure 20). The relative abundance of tall native trees declined rapidly in the post-Māori settlement era, which co-occurred with an increase in bracken fern and charcoal concentration, which are indicative of vegetation disturbance and burning. There was also a steady increase in sedges, and later during this era, the first occurrence and subsequent increase in the wetland plant raupō. After European arrival (c.1840 CE), the native vegetation declined further and was replaced by grasses, while the amount of pollen from non-native trees, such as pine, increased towards the top of the sediment core. The algal proxy from hyperspectral analysis remained relatively constant throughout the record.

The NMDS plot highlights differences in the bacterial composition between human occupation eras. There are marked changes in the composition from approximately halfway through the post-Māori settlement period and late post-European settlement eras (Figure 20). The bacterial functional profiles related to denitrification, dissimilatory nitrate reduction to ammonia and sulphate reduction are variable over time, but there is a small increase in sulphate reduction enzymes post-European arrival.

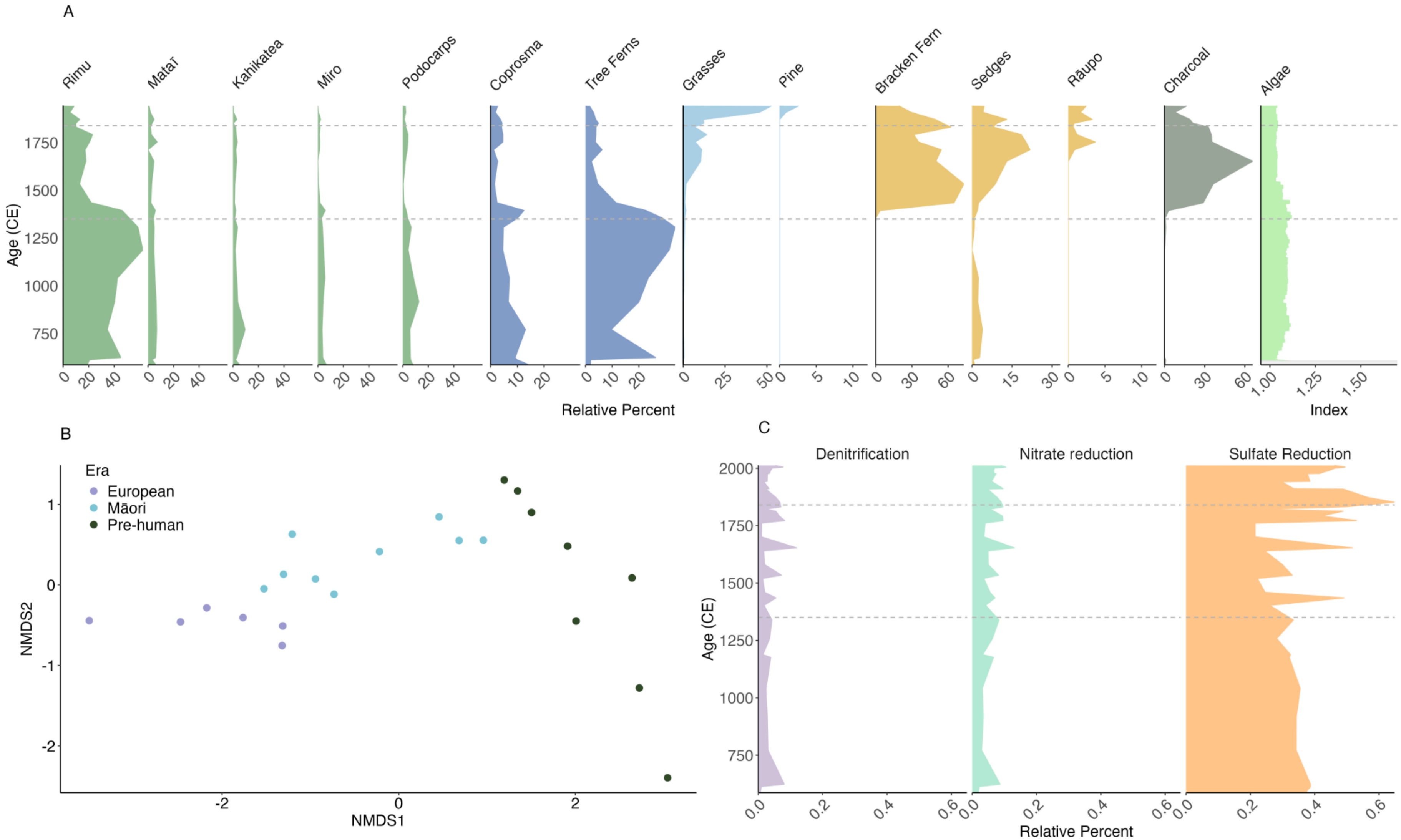


Figure 20. Downcore analysis results for Lake Vincent. (A) Selected relative abundance of pollens (%), charcoal concentration (counts per cm^{-3}), and RABD660-670 index from the hyperspectral analysis (a proxy for algae). (B) Non-metric multi-dimensional scaling ordination plot of the downcore bacterial composition coloured by human occupation era. (C) The proportion of specific metabolic pathways (a portion of functional read abundance) at different depths. The dotted lines represent the different human occupation eras (bottom line: transition from pre-human to Māori settlement; top line: transition to post-European settlement).

6. Summary and recommendations

The analysis of water quality data showed that all three lakes are currently eutrophic. It is important that immediate action is taken to prevent any further degradation of these lakes. This will require ongoing monitoring and targeted studies as outlined in the recommendation section below. This work will help determine the likely causes of degradation and ensure the effective use of resources to enhance protection and restoration.

There was sufficient data for Lake George / Uruwera to undertake a 5-year trend analysis on the most recent data. The analysis showed that most water quality attributes were 'likely degrading'. However, trend results should be interpreted with some caution, as they inform about the direction of a trend but not the magnitude. No trend analysis could be undertaken on the water quality data for Lake Vincent and The Reservoir. A visual inspection of the data showed high levels of variability, reinforcing the need for more regular and long-term monitoring. A positive observation was that although cyanobacteria were present in all lakes, they were in relatively low abundance, and common bloom-forming taxa (e.g. *Microcystis*, *Dolichospermum*) were absent or only present at very low levels.

Analysis of a single surface sediment sample collected from Lake Vincent in January 2019 indicated a high likelihood of internal phosphorus cycling. The paleolimnological analysis of the Lake Vincent sediment core showed there was rapid deforestation around the lake shortly after Māori settled in the region, which caused marked increase in the composition and abundance of wetland species. Concurrently, minor shifts were observed in the aquatic bacterial communities. Despite these changes, the lake likely remained in an oligotrophic to mesotrophic state, characterised by low levels of chlorophyll-*a* (as measured using the hyperspectral scanner). Following European settlement, there was a further decline in native vegetation, leading to changes in the microbial communities. The chlorophyll-*a* remained relatively low and stable, indicating that the decline in water quality in this lake has been relatively recent. The increase in wetland plants may have buffered some of the impacts of deforestation by reducing the amount of sediment and nutrients entering the lake.

The information examined and assessed in the current report provides some understanding of the likely nutrient sources and dynamics within the studied lakes. However, significant data gaps are hindering the development of suitable restoration plans. A summary of data gaps and recommendations for further studies are presented below.

Water quality monitoring

It is imperative that regular monitoring continues at all three lakes. Regular monitoring data were patchy, and there was only sufficient temporal resolution to undertake trend analysis for Lake George / Uruwera. Trend analysis will be a critical component of any future management plan for the lakes. We recommend that monthly water quality monitoring should be conducted at these lakes and continued for at least 5 years.

There are currently two monitoring sites in each of the lakes; however, given that these lakes are all relatively small, we recommend reducing this to one site per lake. The cost and resource savings could be redirected to ensure that the monitoring at each lake is regular, or other lakes in the region could be sampled.

Currently, there is limited or no data on the temporal variability in water column profiles of temperature, dissolved oxygen (DO) and pH. Temperature, DO and pH loggers should be deployed in Lake Vincent and The Reservoir. These should include loggers or sensors for temperature at 2 m intervals, surface and near-bottom DO, and surface pH. Ideally, surface chlorophyll-*a* and surface turbidity sensors should also be included. This would improve knowledge of oxygen and pH dynamics in the lakes and aid in determining the likelihood of internal nutrient cycling (see below). Lake George is shallow and the deployment loggers through the water column is probably not warranted, but deployment of these at the surface would be valuable.

Sediment legacies and internal nutrient loading

Lake Vincent and The Reservoir are vulnerable to internal nutrient loading due to their depths and predicted residence times. A single sample collected from Lake Vincent during the Lakes380 programme also indicates that internal nutrient loading is likely a significant source of phosphorus to this lake. We recommend undertaking further sampling with multiple samples to explore sediment geochemistry and help determine the likelihood of nutrient release from sediments during anoxic or high pH events. This will help in developing nutrient budgets, gaining a better understanding of nutrient release drivers, and guiding potential management interventions.

As noted above, continuous (or at least monthly) water column profiles for temperature and DO should be taken. This regular monitoring would provide data on the duration of stratification, which directly affects internal loading potential, and inform potential management interventions such as oxygenation / circulation.

External nutrient loading

CLUES modelling was carried out for the three studied lakes by Kelly et al. (2013). Due to restrictions on access, we were unable to update these models; therefore, we suggest commissioning the authors of CLUES (NIWA) to update this work.

In addition to high-level CLUES modelling, it is important to determine the nutrient loading from the catchment. Understanding the primary nutrient transport pathways specific to each lake is essential for targeting suitable mitigation and restoration measures. It would be valuable to develop water balance models specific to each lake. These models should incorporate surface and groundwater data (inflows/outflows, surface and groundwater connectivity, direct rain inputs and evapotranspiration, lake level), and continuous monitoring of lake levels is crucial for this work. Nutrient loads from bird excreta may also be significant in some lakes. While there is information in the literature on the nutrient contents of various bird excreta and the likely volume per bird, there is a lack of data on the number of birds at the focal lakes. Conducting regular bird counts could be included as part of the monitoring effort.

The collection of external and internal nutrient and high-frequency data may allow lake modelling to be undertaken in the future, noting that additional data such as meteorological information would be required. The development of lake models would allow management scenarios to be better explored.

Macrophytes

The current data are not sufficient to identify patterns in macrophyte cover and / or community composition. We suggest that macrophyte monitoring (LakeSPI) should be carried out at least once every 5 years. Macrophytes play a crucial role in structuring lake ecosystems and in absorbing and retaining nutrients. Therefore, in addition to long-term monitoring of aquatic vegetation trends, it is important to understand the seasonal changes in macrophytes, with a focus on their susceptibility to collapse and their impact on nutrient cycling. We therefore also suggest conducting one-time seasonal surveys of macrophyte biovolume to determine the degree to which macrophyte die-back contributes to lake anoxia cycles (every quarter). Cost-effective methods, such as side-scan sonar transects, could be used.

Fish and biodiversity

The last comprehensive biodiversity surveys were undertaken in these three lakes over a decade ago. Current data are insufficient to determine trends in fish density or changes in species present. This information would be useful for assessing trends in ecological conditions as well as potential impacts on nutrient cycling and invasive species. We recommend that standardised fish surveys should be conducted every 5 years.

Biodiversity data and food web analysis would provide some insight into possible 'trophic cascade' effects. For example, analysis of zooplankton dynamics might identify their impact on phytoplankton, or the effect of perch on zooplankton.

Further paleolimnological analysis

Further analysis could be undertaken on the Lake Vincent sediment core to explore changes in biodiversity and the drivers of these changes. These data would also be useful in setting informed restoration targets, such as identifying which fish species were present in the lake 100 years ago. Possible parameters that could be analysed are provided in Table 4. Unfortunately, due to the shallow nature of Lake George / Uruwera, collecting a sediment core was challenging. It is also likely that the sediment is mixed and the stratification of the sediment may be mixed; therefore, we recommend caution if any paleolimnological studies are undertaken on the sediment core from Lake George / Uruwera.

Table 4. Description of methods that could be applied to the Lake Vincent sediment core.

Proxy (method)	Information provided
Itrax scanning – entire core is scanned	Indications of shifts in lake geochemistry, productivity and catchment erosion.
Diatoms	Indicate changes in water quality and other parameters such as depth and light availability.
Cadmium	A proxy for fertiliser application on land surrounding the lake. Cadmium is found in phosphate rocks, which are used to make fertilisers such as superphosphate.
Lead	A proxy for increases in population or urbanisation close to a lake. The lead is likely sourced from leaded petrol, which was phased out in Aotearoa New Zealand in 1996.
Environmental DNA – biodiversity	Provides insights into changes in biodiversity in the lake and land around the lake. For example, we could focus on macrophytes, mammals and fish.

7. Appendices

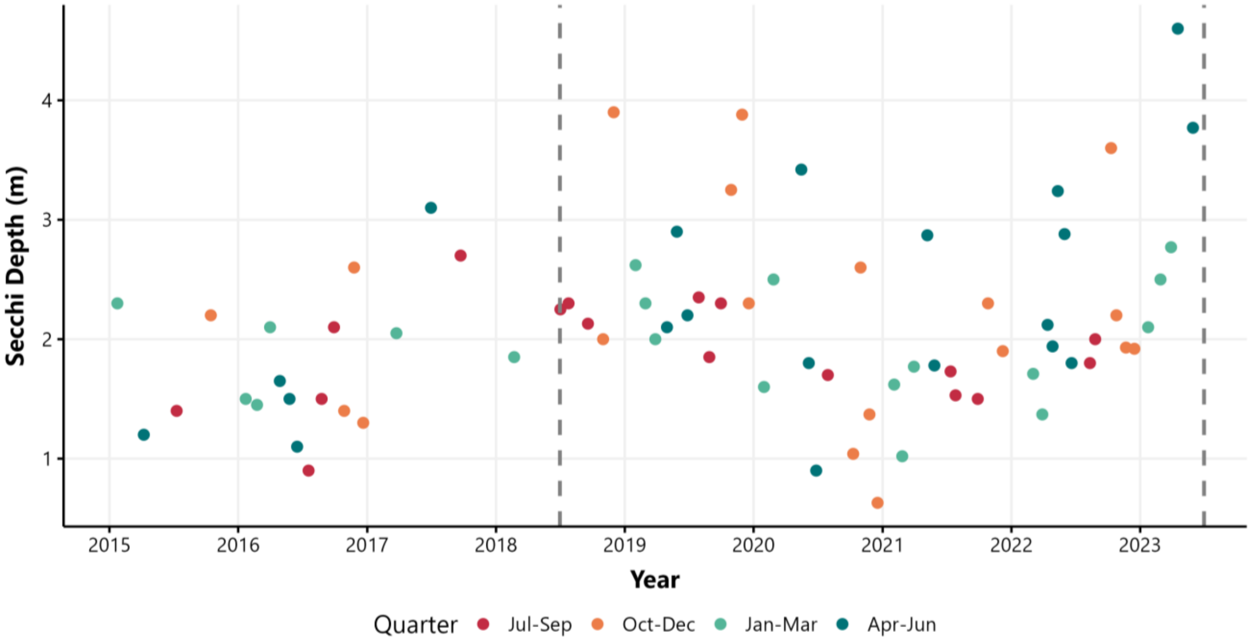


Figure A1. Lake Vincent – Central site. Secchi Disc depth (visual clarity) across the dataset. The vertical grey lines represent the last 5 years of data.

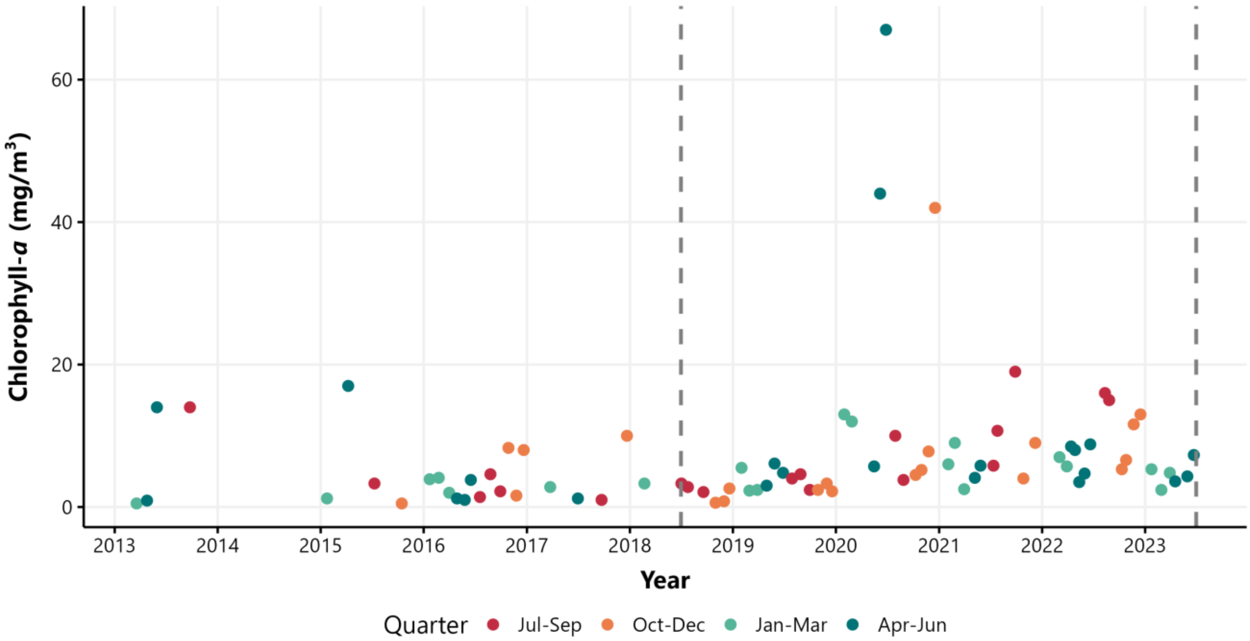


Figure A2. Lake Vincent – Central site. Chlorophyll-*a* depth (visual clarity) across the dataset. The vertical grey lines represent the last 5 years of data.

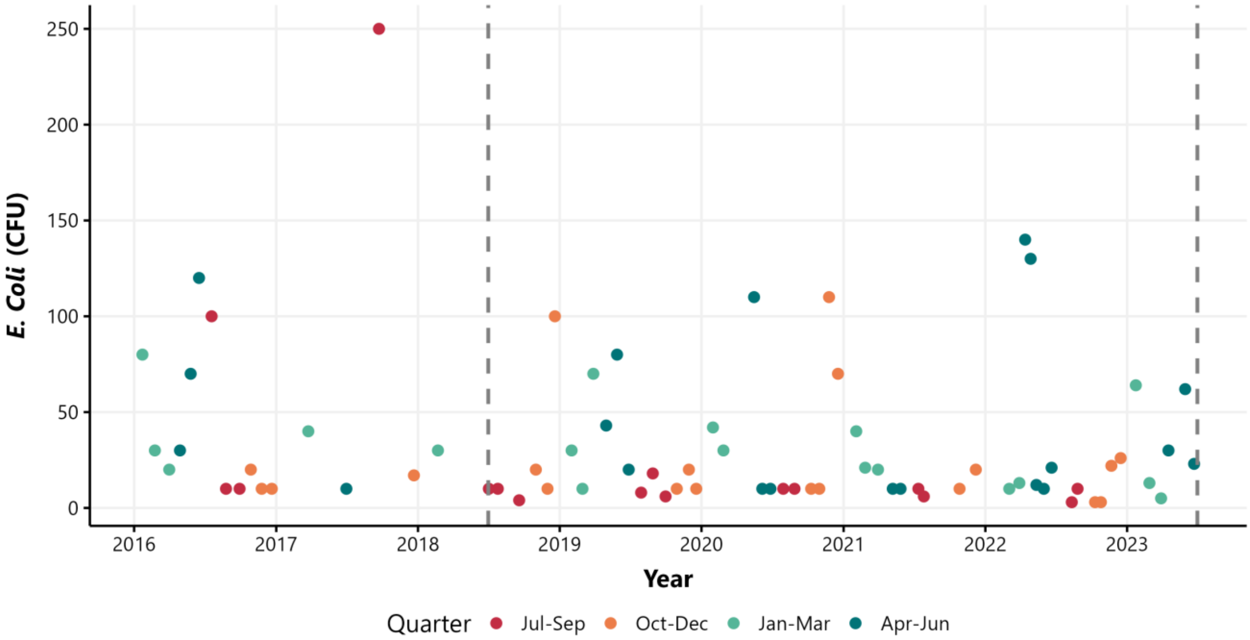


Figure A3. Lake Vincent – Central site. *E. coli* concentrations across the dataset. The vertical grey lines represent the last 5 years of data.

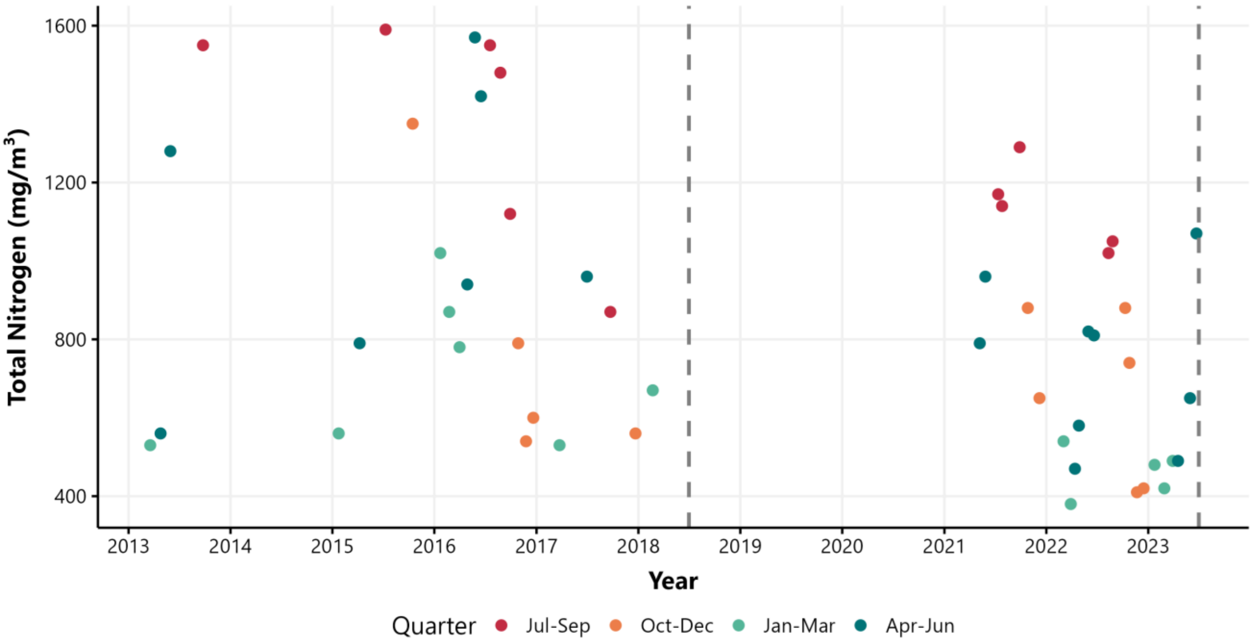


Figure A4. Lake Vincent – Central site. Total nitrogen plotted over time. The vertical grey lines represent the last 5 years of data.

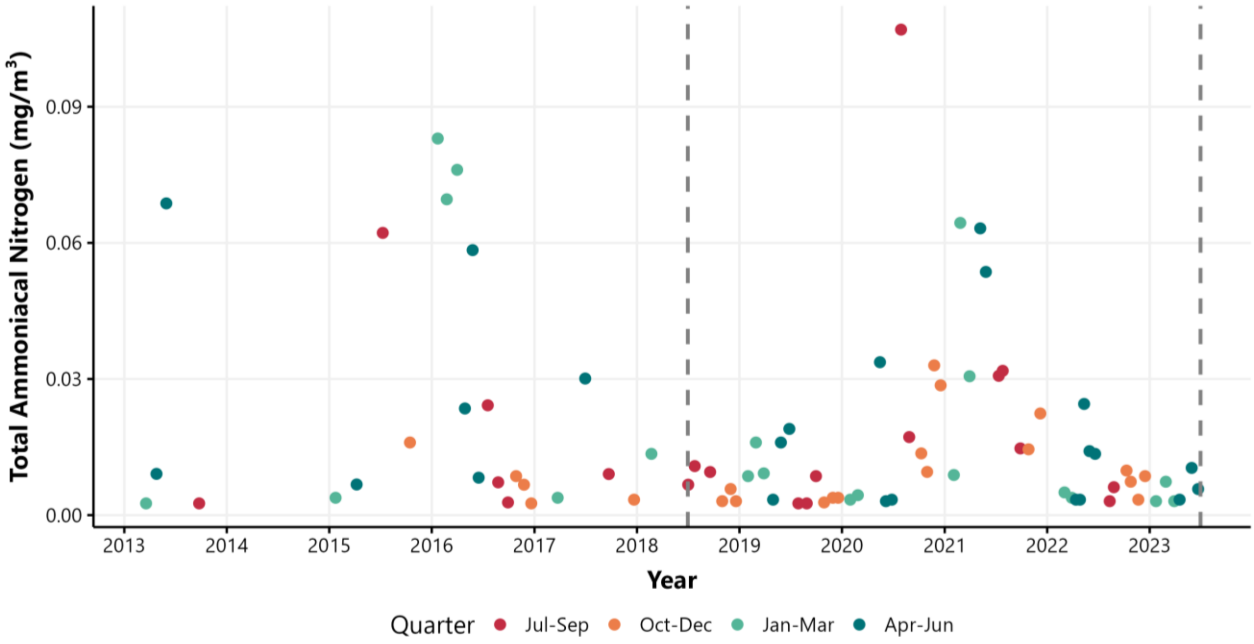


Figure A5. Lake Vincent – Central site. Ammoniacal nitrogen (pH adjusted) plotted over time The vertical grey lines represent the last 5 years of data.

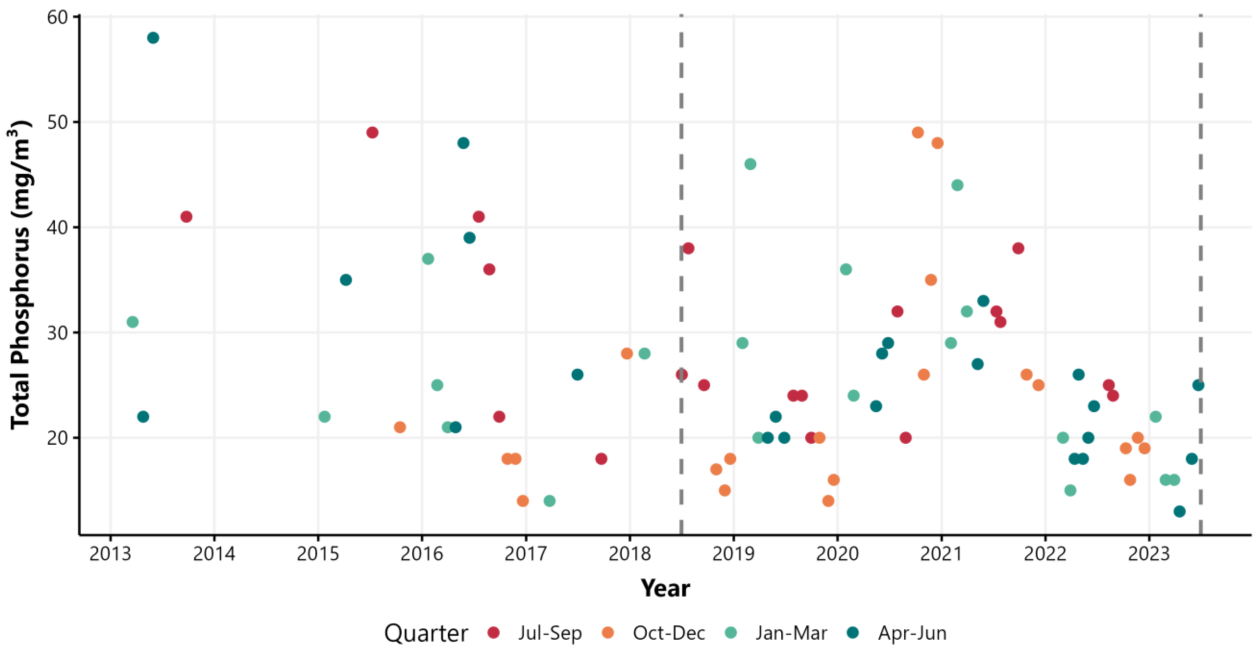


Figure A6. Lake Vincent – Central site. Total phosphorus concentrations plotted over time. The vertical grey lines represent the last 5 years of data.

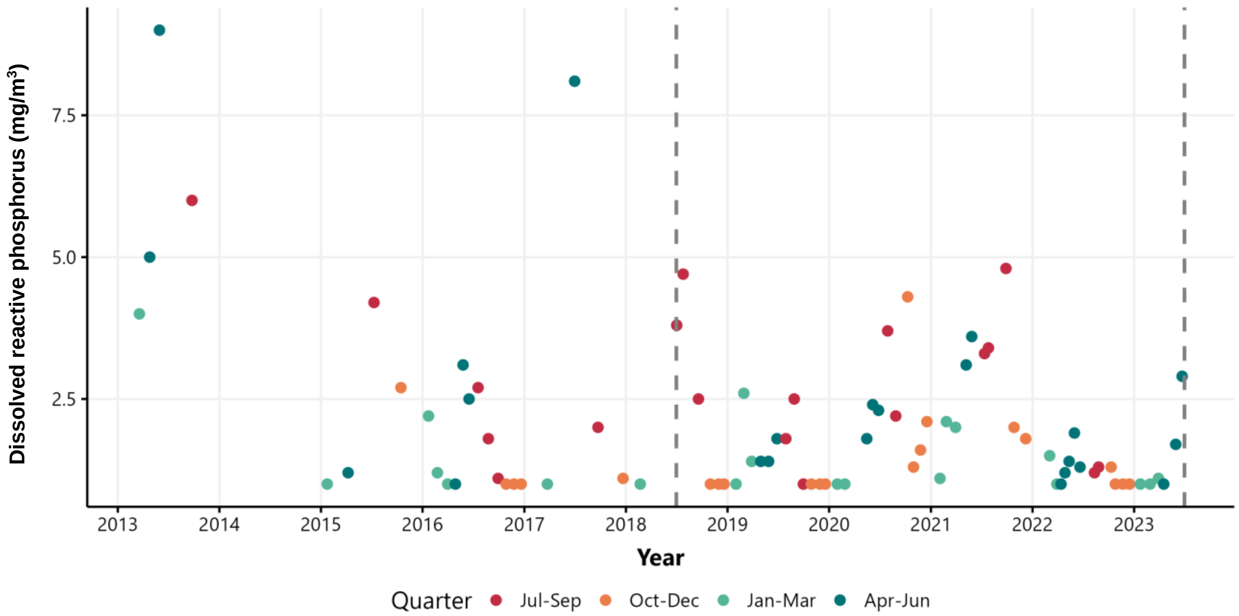


Figure A7. Lake Vincent – Central site. Dissolved reactive phosphorus concentrations plotted over time. The vertical grey lines represent the last 5 years of data.

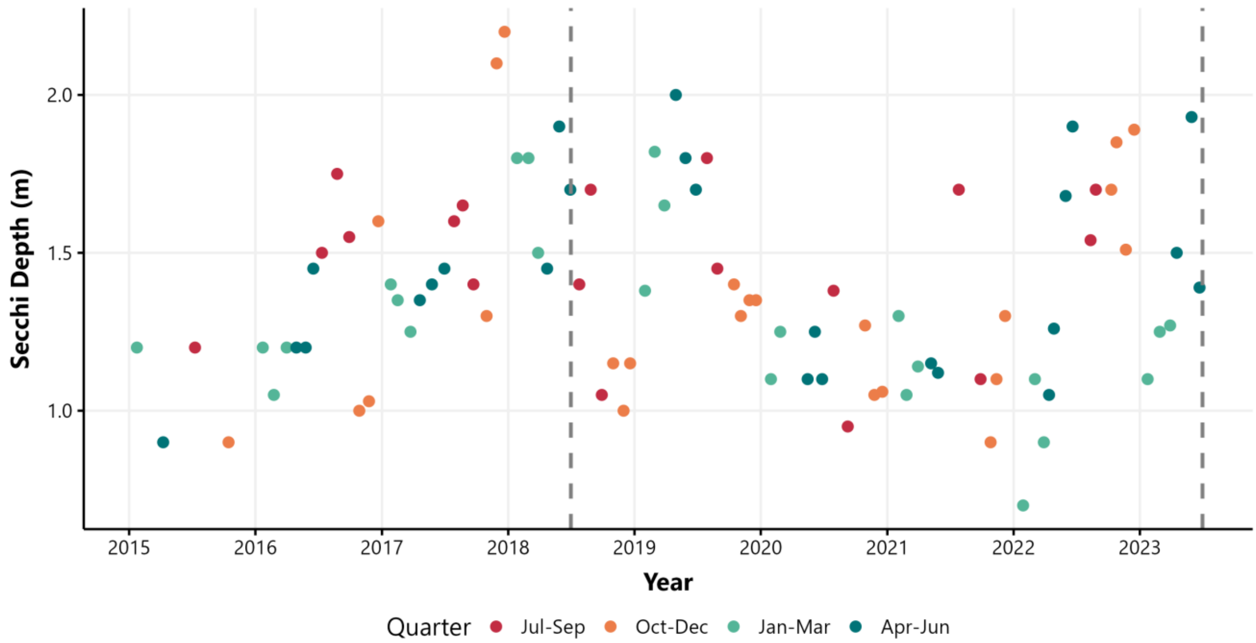


Figure A8. The Reservoir – Central site. Secchi Disc depth (visual clarity) across the dataset. The vertical grey lines represent the last 5 years of data.

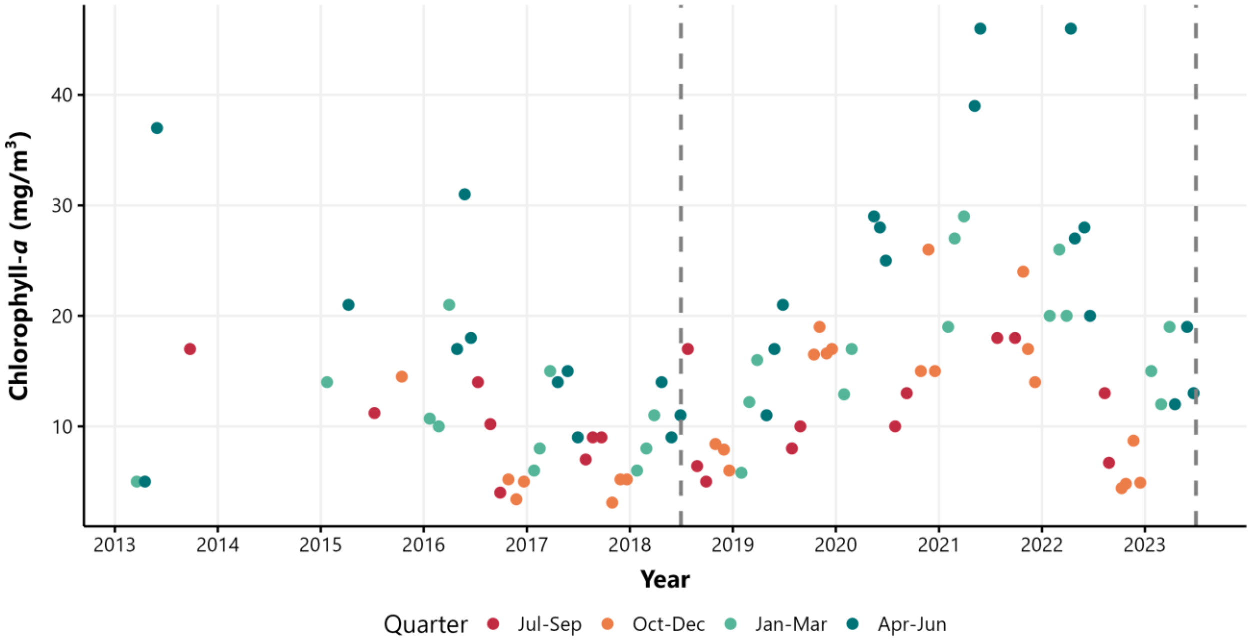


Figure A9. The Reservoir – Central site. Chlorophyll-*a* depth (visual clarity) across the dataset. The vertical grey lines represent the last 5 years of data.

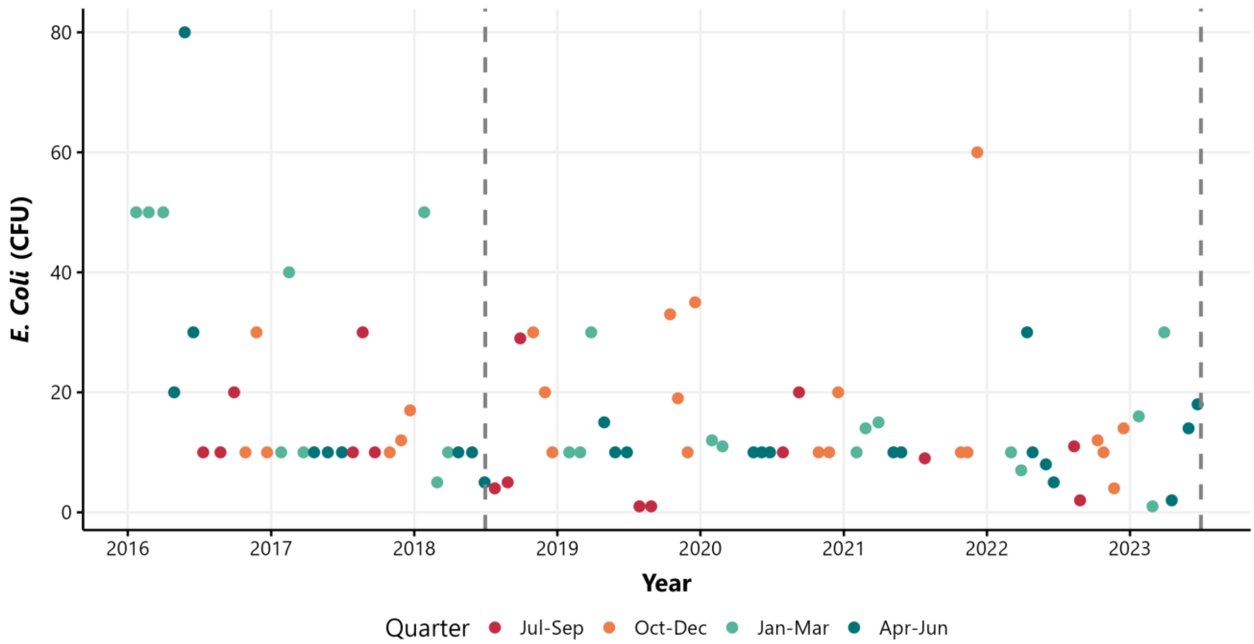


Figure A10. The Reservoir – Central site. *E. coli* concentrations across the dataset. The vertical grey lines represent the last 5 years of data.

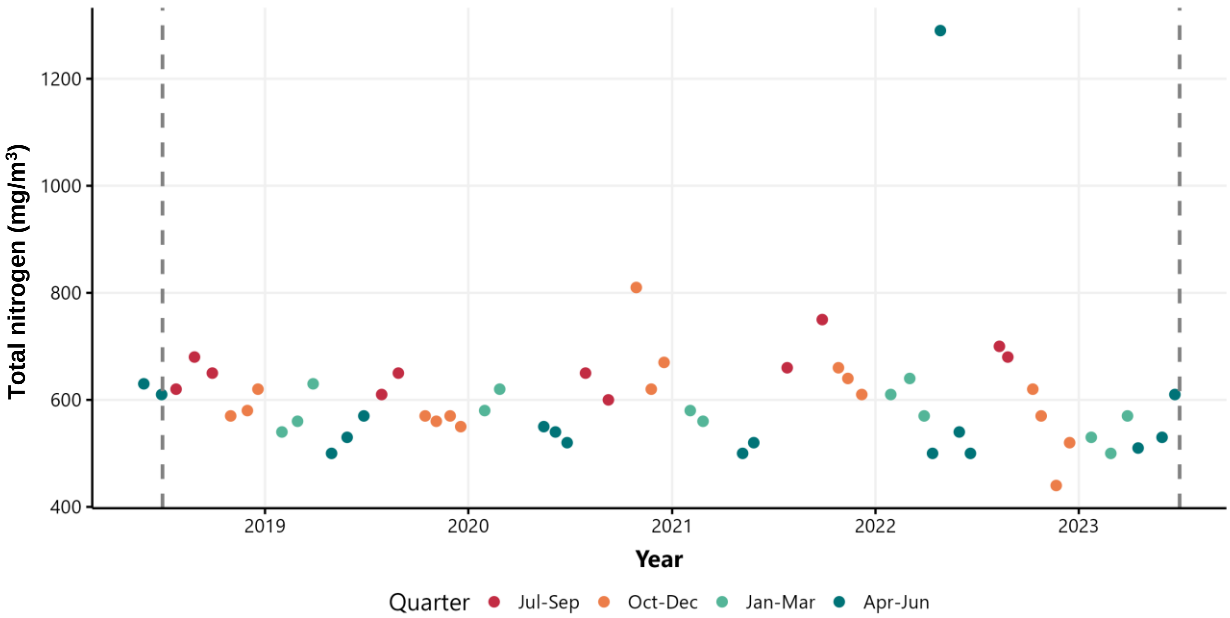


Figure A11. The Reservoir – Central site. Total nitrogen plotted over time. The vertical grey lines represent the last 5 years of data.

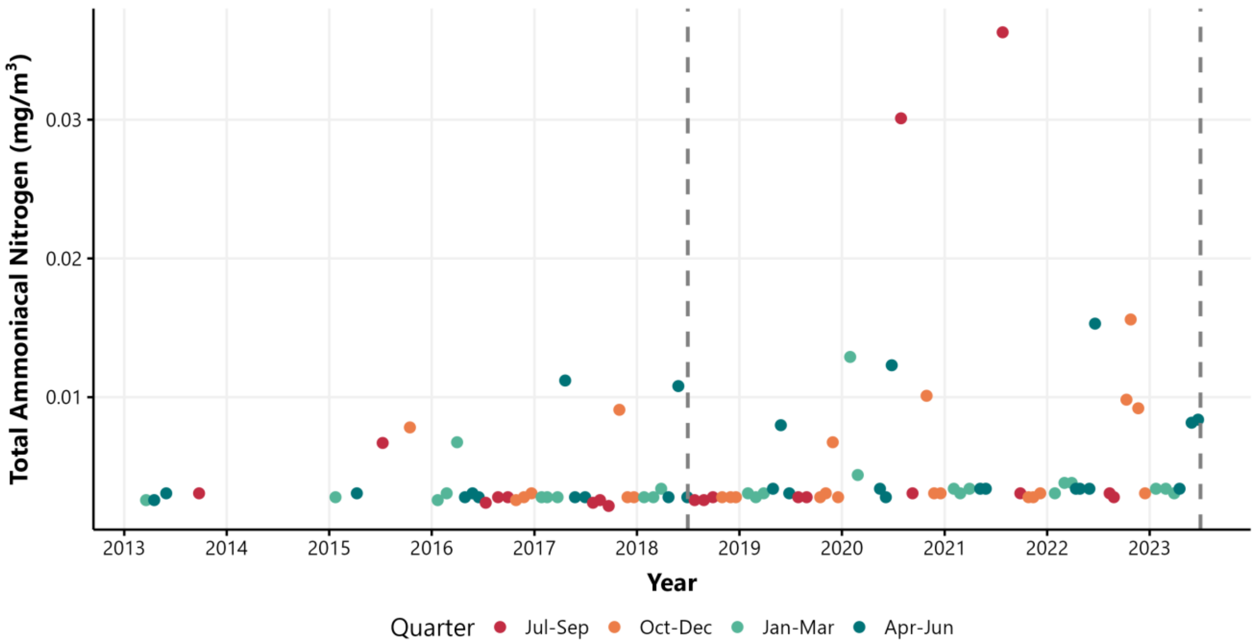


Figure A12. The Reservoir – Central site. Ammoniacal nitrogen (pH adjusted) plotted over time The vertical grey lines represent the last 5 years of data.

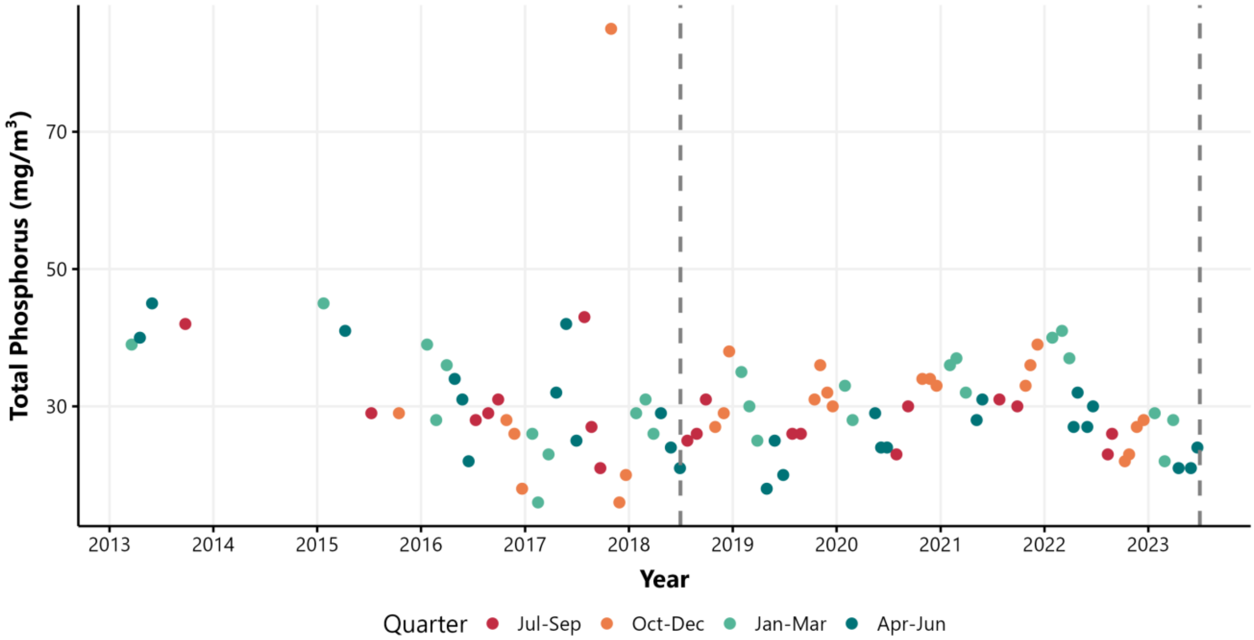


Figure A13. The Reservoir – Central site. Total phosphorus concentrations plotted over time. The vertical grey lines represent the last 5 years of data.

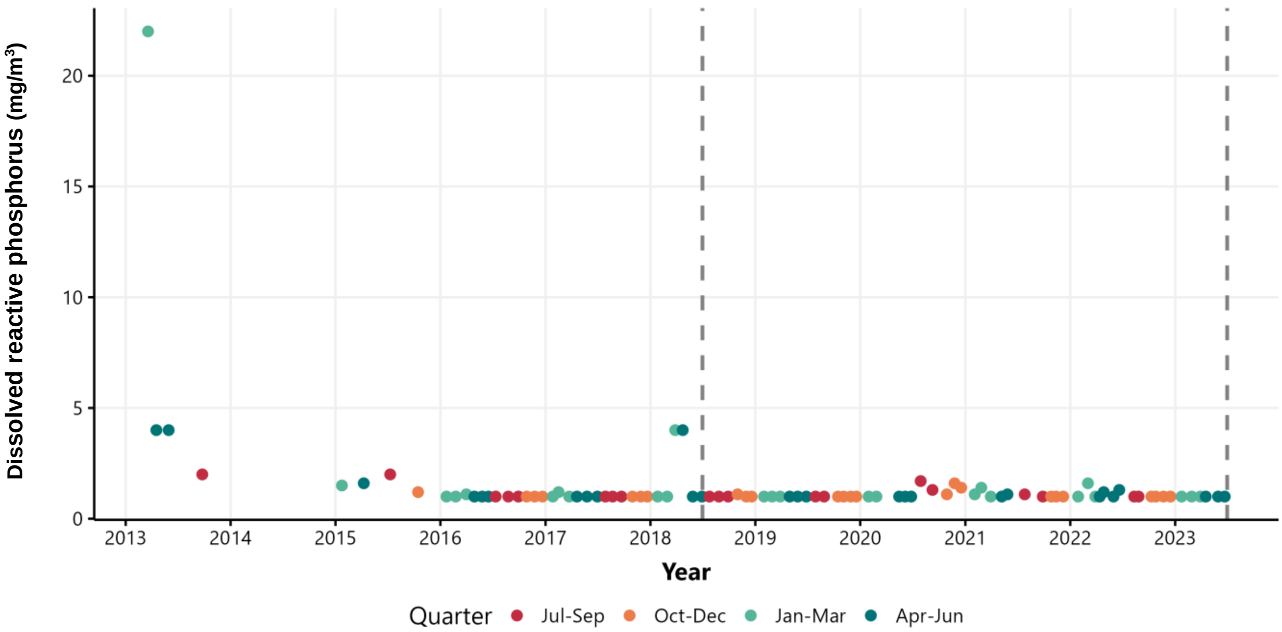


Figure A14. The Reservoir – Central site. Dissolved reactive phosphorus concentrations over time. The vertical grey lines represent the last 5 years of data.

8. References

Baisden W, Prior C, Chambers D, Canessa S, Phillips A, Bertrand C, Zondervan A, Turnbull J, Kaiser J, Bruhn F. 2013. Rafter radiocarbon sample preparation and data flow: accommodating enhanced throughput and precision. Nuclear Instruments and Methods in Physics Research. Section B: Beam Interactions with Materials and Atoms. 294:194–198.

Bowman JS, Ducklow HW. 2015. Microbial communities can be described by metabolic structure: a general framework and application to a seasonally variable, depth-stratified microbial community from the coastal West Antarctic Peninsula. PloS One. 10(8):e0135868.

Hogg AG, Heaton TJ, Hua Q, Palmer JG, Turney CS, Southon J, Bayliss A, Blackwell PG, Boswijk G, Ramsey CB. 2020. SHCal20 Southern Hemisphere calibration, 0–55,000 years cal BP. Radiocarbon. 62(4):759–778.

Kelly D, Shearer K, Schallenberg M. 2013. Nutrient loading to shallow coastal lakes in Southland for sustaining ecological integrity values. Nelson: Cawthron Institute. Cawthron Report 2375. Prepared for Environment Southland.

[LWP] LandWaterPeople. 2021. Water quality trend analysis functions for R: the LWP-Trends library to undertake water quality trend analysis in the R statistical computing environment (updated 17 November 2021). https://landwaterpeople.co.nz/pdf_report/water-quality-trend-analysis-functions-for-r/

Leathwick J, West D, Gerbeaux P, Kelly D, Robertson H, Brown D, Chadderton W, Ausseil A. 2010. Freshwater ecosystems of New Zealand (FENZ) geodatabase. Users guide. Wellington: Department of Conservation.

McGlone MS, Wilmshurst JM, Leach HM. 2005. An ecological and historical review of bracken (*Pteridium esculentum*) in New Zealand, and its cultural significance. New Zealand Journal of Ecology. 29(2):165–184.

McGlone MS, Wilmshurst JM. 1999. Dating initial Maori environmental impact in New Zealand. Quaternary International. 59(1):5–16

McWethy DB, Whitlock C, Wilmshurst JM, McGlone MS, Fromont M, Li X, Dieffenbacher-Krall A, Hobbs WO, Fritz SC, Cook ER. 2010. Rapid landscape transformation in South Island, New Zealand, following initial Polynesian settlement. Proceedings of the National Academy of Sciences. 107(50):21343–21348.

[MfE] Ministry for the Environment. 2024. National Policy Statement for Freshwater Management 2020. Amended January 2024. Wellington: Ministry for the Environment.

Newnham R, Lowe DJ, Gehrels M, Augustinus P. 2018. Two-step human–environmental impact history for northern New Zealand linked to late-Holocene climate change. The Holocene. 28(7):1093–1106.

Pearman JK, Biessy L, Thomson-Laing G, Water S, Vandergoes MJ, Howarth JD, Rees A, Moy C, Pochon X, Wood SA. 2020. Local factors drive bacterial and microeukaryotic community composition in lake surface sediment collected across an altitudinal gradient. FEMS Microbiology Ecology. 96(6):70–83.

Ramsey CB. 2008. Deposition models for chronological records. Quaternary Science Reviews. 27(1–2):42–60.

Ramsey CB. 2009. Bayesian analysis of radiocarbon dates. Radiocarbon. 51(1):337–360.

Ramsey CB, Lee S. 2013. Recent and planned developments of the program OxCal. Radiocarbon. 55(2):720–730.

Rydin E. 2000. Potentially mobile phosphorus in Lake Erken sediment. Water Research. 34(7):2037–2042.

Schallenberg M, Kelly D. 2012. Ecological condition of six shallow southland lakes. Nelson: Cawthron Institute. Cawthron Report No 2198. Prepared for Environment Southland.

Schallenberg M, Kelly D. 2013. Estimates of reference conditions for Southland's shallow, lowland lakes. Invercargill: Hydrosphere Research Ltd. Prepared by for Environment Southland Environment Southland.

Turnbull JC, Mikaloff Fletcher SE, Brailsford GW, Moss RC, Norris MW, Steinkamp K. 2017. Sixty years of radiocarbon dioxide measurements at Wellington, New Zealand: 1954–2014. Atmospheric Chemistry and Physics. 17(23):14771–14784.

Waters S, Verburg P, Schallenberg M, Kelly D. 2021. Sedimentary phosphorus in contrasting, shallow New Zealand lakes and its effect on water quality. New Zealand Journal of Marine and Freshwater Research. 55(4):592–611.

World-class science for a better future.

CAWTHRON

98 Halifax Street East, Nelson 7010 | Private Bag 2, Nelson 7042 | New Zealand | Ph. +64 3 548 2319

cawthron.org.nz