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Investigating internal phosphorus loading potential in Lake Ngatu with comparisons to other Northland lakes

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Investigating internal phosphorus loading potential in Lake Ngatu with comparisons to other Northland lakes

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Northland Regional Council

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Glossary

Term	Definition
Anoxic	A complete absence of dissolved oxygen in water.
Bioavailable (e.g. phosphorus)	The extent to which nutrients are in forms that can be absorbed and used by living organisms. Nutrients may be 'bioavailable' – readily taken up by organisms – or exist in non-bioavailable forms that are not accessible for biological uptake.
Epilimnion	The top layer of water in a thermally stratified lake. The epilimnion is typically characterised by warm water and high oxygen concentrations due to direct contact with the atmosphere.
Eutrophic lake	A lake with high phytoplankton productivity driven by elevated levels of nutrients such as nitrogen and phosphorus. Eutrophic lakes often experience low dissolved oxygen levels in their bottom waters, as frequent algal and cyanobacterial blooms fuel increased heterotrophic activity (e.g. decomposition) in the hypolimnion, leading to greater bacterial respiration in the sediments.
External loading	The process by which nutrients enter the lake from surrounding land, via precipitation, and other sources like run-off and wastewater.
Hypolimnion	The dense, cold and deep layer of a thermally stratified lake that typically remains cooler and has lower oxygen levels than the layers above.
Polymictic lake	A lake in which the water column undergoes frequent stratification and multiple mixing events within a single year due to its small size and shallow depth.
Internal loading	The process by which phosphorus and nitrogen are released from lakebed sediments into the hypolimnion (bottom waters) of lakes under low dissolved oxygen and elevated pH conditions.
Mesotrophic lake	A lake with a moderate nutrient level and phytoplankton productivity. These lakes can experience low dissolved oxygen levels in their bottom waters due to a higher number of heterotrophic processes (e.g. decomposition) occurring in the hypolimnion.
Oligotrophic lake	A lake with a low nutrient level and phytoplankton productivity, with high oxygen concentrations throughout the water column due to its lower organic content compared to eutrophic lakes.
Supertrophic lake	A lake with very high algal productivity due to excessive nutrient concentrations. These lakes are highly susceptible to frequent algal and cyanobacterial blooms, which can lead to oxygen depletion in the hypolimnion due to increased heterotrophic activity, such as decomposition.
Thermal stratification	The process by which a lake develops distinct layers due to temperature differences between them. During summer, the lake water column typically separates into the epilimnion (warm, light surface water) and the hypolimnion (cold, dense bottom water).

Contents

Executive summary

This report provides an assessment of the contribution of internal phosphorus (P) loading in Lake Ngatu, with a focus on thermal stratification, oxygen depletion, redox-sensitive sediment-bound P and nitrogen (N). Data sources include long-term discrete monitoring (1996–22), high-frequency buoy measurements (2022–25), and laboratory sediment analyses of samples collected in November 2018 as part of the Lakes380 (contract C05X1707) research programme. The sediment characteristics in Lake Ngatu were also benchmarked against 26 other Northland dune lakes.

Lake Ngatu experiences seasonal thermal stratification, particularly during the spring and summer months, when surface temperatures exceed bottom temperatures by more than 1 °C. Historical discrete data show oxygen concentrations remained above the National Policy Statement for Freshwater Management 2020 (NPS-FM) bottom line (> 4 $mg{\cdot}L^{-1}$); however, continuous monitoring revealed at least 11 short-term anoxic events (O_2 < 2 $mg{\cdot}L^{-1}$) between 2022 and 2025. The mean rate of bottom water oxygen depletion was −0.6 ± 0.2 $mg\,O_2{\cdot}L^{-1}{\cdot}day^{-1}$, with stratification periodically interrupted by wind-induced mixing. The most rapid oxygen depletion occurred in summer 2022–23 (−0.8 $mg\,O_2{\cdot}L^{-1}{\cdot}day^{-1}$).

Sediment analysis showed that 53.1% of the total P pool is in bioavailable forms, primarily organic P (40.6%), with minimal exchangeable (0.6%) and redox-sensitive (2.1%) fractions. Compared to other Northland lakes, Lake Ngatu has one of the lowest concentrations of bioavailable P (ranked sixth out of 27 lakes), and its total sedimentary P content (1,034 $mg\ P{\cdot}kg^{-1}$ DW) is well below the regional average (1,682 ± 844 $mg\ P{\cdot}kg^{-1}$ DW). Similarly, pore-water P concentrations and equilibrium P concentrations (0.004 $mg{\cdot}L^{-1}$) were low, indicating limited potential for P flux from sediment to the water column under stable conditions.

Laboratory incubations under anoxic conditions (‘glove box’ experiment) showed elevated potential areal P release rates (105.9 $mg{\cdot}m^{-2}{\cdot}d^{-1}$) – approximately three times higher than the average rate observed in other Northland dune lakes – under conditions of an extreme future perturbation, such as elevated organic loading and physical disturbance. Under current conditions, sediment characteristics in Lake Ngatu suggest a low risk of sustained internal P loading. High sediment density, elevated aluminium concentrations and low equilibrium P concentrations, along with low pore-water total and dissolved reactive P, all point to the lakebed acting as a P sink rather than a source.

While short-lived anoxic events and wind-induced mixing may occasionally trigger internal P release, the sediment in Lake Ngatu generally appears to be buffering the lake from adverse impacts of elevated catchment nutrient loading.

To improve understanding and management of drivers of eutrophication in Lake Ngatu, the following recommendations are provided:

- Develop a full water budget for the lake, including groundwater inputs and nutrient concentrations.
- Continue high-frequency oxygen, temperature and pH monitoring.
- Quantify external nutrient loads, particularly from stormwater and wastewater.
- Deploy sediment traps and assess macrophyte biomass and nutrient content.
- Investigate the effect of wind stress on full-lake mixing and nutrient resuspension.

This study combined long-term as well as high-frequency data from Lake Ngatu to support and complement region-wide sediment data and national lake water quality models. The information gained from this, and subsequent studies in Lake Ngatu provide a regional case study that can inform a region-wide lake triage assessment and action prioritisation framework.

1. Introduction

The Northland Regional Council (NRC) requested that Cawthron Institute conduct an analysis of the sediment nutrient composition of Lake Ngatu, and a comparison with the sediment conditions of 26 other Northland lakes, to better understand the lake's vulnerability to internal nutrient loading.

Lake Ngatu is a relatively large dune lake in the Northland Region of Aotearoa New Zealand (Figure 1), covering a surface area of 55.3 hectares and reaching a maximum depth of 6.1 metres. It has no surface outflow and receives water primarily by rainfall and surface run-off. Lake Ngatu is a polymictic lake that is frequently mixed by wind due to its shallow depth, and it only remains thermally stratified for short periods, typically lasting 10 days or less. Lake Ngatu is classified as eutrophic and has exhibited Trophic Level Index (TLI) scores indicating fair to poor water quality over the monitoring period from 2009 to 2023. In the last 5 years, nutrient concentrations have increased and the lake has experienced several algal bloom events.[1] Noticeable high concentrations of phytoplankton biomass (measured as chlorophyll-*a*) were recorded for Lake Ngatu in 2009 (> 20 $ug \cdot L^{-1}$), 2015 (> 35 $ug \cdot L^{-1}$), 2020 (> 30 $ug \cdot L^{-1}$), and 2022 (> 80 $ug \cdot L^{-1}$). Currently, the lake supports a 'high value' native macrophyte community;[2] however, further algal blooms may trigger a regime shift in the lake and negatively impact diverse communities of submerged macrophytes by reducing light availability due to dense surface algal growth, necessitating the need to reduce nutrient concentrations in the lake (NRC 2015).

Land use in the catchment surrounding Lake Ngatu – including a low number of houses, perennial crops, and dairy, sheep and beef farmland – has a direct influence on the lake. Dairy farming accounts for 33% of the catchment land area but contributes 72% of the nitrogen (N) and 63% of the phosphorus (P) loads.[3] In comparison, sheep and beef farming cover 29% of the catchment and contribute 25% of the N and 31% of the P loads, highlighting the dominant role of intensive land use in nutrient loading to the lake. Moreover, nutrient loads from septic tank sources may be underestimated due to the ageing and potentially inefficient infrastructure built for the historic urban development around Lake Ngatu. This includes older septic systems, increased stormwater run-off from roads, and nearby facilities such as a school and Department of Conservation toilets – both of which are serviced by outdated wastewater systems (Kuczynski et al. 2024).

Sediment processes and nutrient dynamics can play a significant role in driving a lake's primary productivity. Different forms of P bound to sediments can vary in their bioavailability – some forms can be readily recycled into the water column under certain conditions (and subsequently fuel algal growth), while others are in stable forms that remain bound to the sediment under a wide range of conditions (Rydin 2000). In shallow lakes, frequent interaction between the water column and the sediment surface under diverse physical and chemical conditions can promote the release of nutrients from the sediment. Wind mixing can drive sediment resuspension, a physical sediment nutrient flux process. Chemical release is often triggered by conditions such as low oxygen (redox sensitive) or elevated pH (pH sensitive), which can cause P mobilisation into the water column (Figure 2). The onset of these conditions can make lake sediments a source of P, sustaining or contributing to lake eutrophication

[1] https://www.lawa.org.nz/explore-data/northland-region/lakes/lake-ngatu [accessed 9 May 2025]
[2] https://www.nrc.govt.nz/media/sgeno0uw/120-lake-ngatu-te-hiku-2023.pdf [accessed 12 June 2025]
[3] https://www.freshwater-scenario-builder.co.nz/lakes [accessed 29 May 2025]

(Søndergaard et al. 2003). Thus, nutrient release from sediments is a concern because it can internally load lakes with phosphorus (P), fuelling algal blooms and degrading water quality – even when external inputs are reduced.

For this report, sediment data for Lake Ngatu and other Northland lakes were sourced from the Lakes380 programme, which involved the collection of sediment cores, water quality data and cultural knowledge from lakes across Aotearoa New Zealand, including those in Northland.[4] We used these data to improve our understanding of sediment properties, nutrient dynamics and sediment–water interactions, all of which are crucial for evaluating lake health.

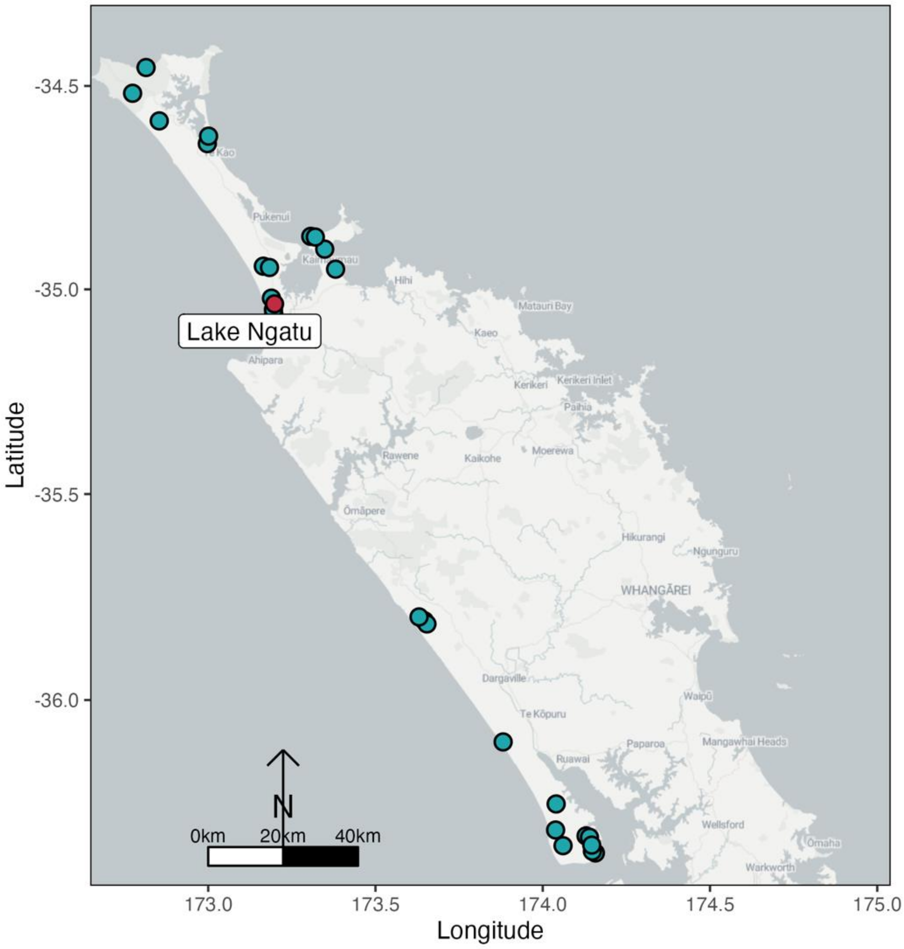

Figure 1. Map of Lake Ngatu (red dot) and other Northland dune lakes (blue dots) reviewed in this report. These lakes were surveyed as part of the Lakes380 programme in 2018 and 2019.

[4] For further information, see: https://ourlakesourfuture.co.nz/lakes/

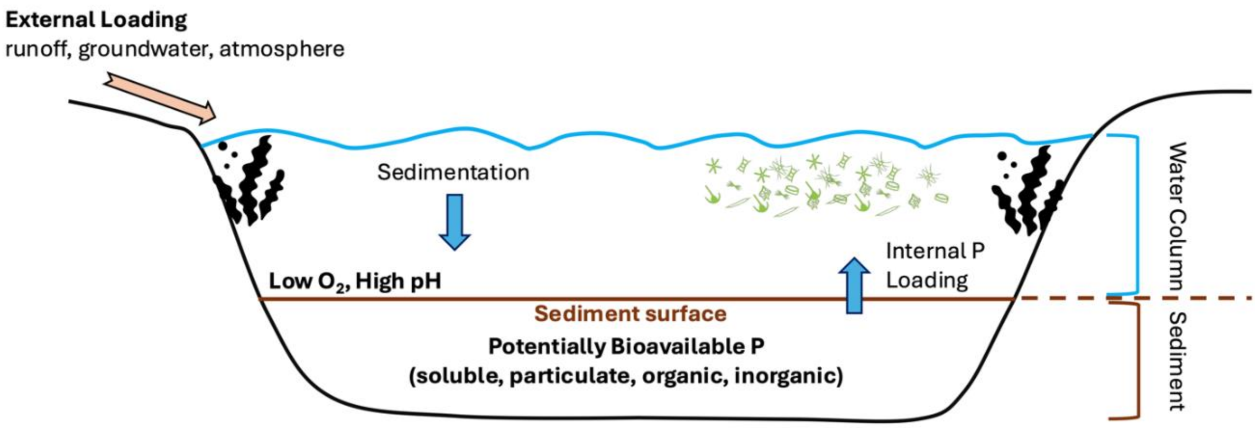

Figure 2. Schematic diagram of the phosphorus (P) cycle in a dune lake.

2. Materials and methods

2.1 Study sites

Lake Ngatu is a perched Class 1[5] lake, formed as an elevated deflation hollow, with a modelled inflow of 715,553 m^3 per year. Its estimated residence time is 1.6 years (NRC 2018), which is considered relatively short (Wetzel 2001). The lake is surrounded by a narrow fringe of shallow wetland but is not connected to any other waterbodies, despite being in close proximity to several small dune lakes. Along with Lake Ngatu, a further 26 Northland dune lakes that had available sediment data from the Lakes380 programme were included in this report to investigate sediment biochemistry (Table 1).

Table 1. List of Northland dune lakes reviewed in this report.

Lake name	Location (latitude, longitude)	Sediment sampling date	Surface area (ha)	Maximum depth (m)	Trophic state*
Ngatu	-35.0355278, 173.1982987	11/12/2018	55.3	6.1	Eutrophic
Katawich	-34.943127, 173.164791	7/5/2019	6.9	0.9	Eutrophic
Waiparera	-34.94642884, 173.1832282	7/5/2019	108.6	6.5	Supertrophic
Wainui	-36.10130034, 173.8816115	8/17/2019	4.6	11.5	Supertrophic
Rotopokaka	-34.950534, 173.380711	7/2/2019	11.7	4.5	Mesotrophic
Waipara	-34.58615, 172.8536833	11/13/2018	2	4.8	Mesotrophic
Ngakeketo	-34.51811622, 172.7739775	6/25/2019	8.9	15.2	Eutrophic
Taharoa	-35.80788333, 173.6462167	11/6/2018	210.2	38	Oligotrophic
Kai-iwi	-35.81565, 173.6538167	11/6/2018	27.9	15	Mesotrophic
Waikare	-35.7986, 173.6303	8/20/2019	29.6	30	Oligotrophic
Rotoroa	-35.05901108, 173.1958266	7/1/2019	32.2	7.5	Eutrophic
Heather	-35.0492848, 173.1949957	7/1/2019	8.3	4.5	Eutrophic
Carrot	-35.0214519, 173.1889745	11/12/2018	2.7	7.8	Eutrophic
Waiporohita	-34.90133333, 173.3482167	11/11/2018	6.1	3.7	Supertrophic
Rotokawau(Karikari)	-34.87002263, 173.3064349	7/8/2019	69.7	1.5	Mesotrophic
24423	-34.87172436, 173.3201327	7/8/2019	21.5	0.8	Eutrophic
Waitahora	-34.45466, 172.81425	6/27/2019	2.1	2.5	Supertrophic
Morehurehu	-34.64216655, 172.9973286	11/14/2018	48.7	14.1	Mesotrophic
Te Kahika	-34.62373575, 173.0010867	11/14/2018	14.4	10.8	Oligotrophic
Mokeno	-36.35158, 174.06073	11/8/2018	161.6	6.2	Supertrophic
Karaka	-36.31386667, 174.0384667	11/8/2018	11.9	5.8	Eutrophic
Rototuna	-36.25107, 174.04008	11/15/2018	6.9	3.5	Eutrophic
Kahuparere	-36.36910358, 174.1573594	8/14/2019	6.9	7	Eutrophic
Kanono	-36.36485, 174.1484167	11/15/2018	75.6	14.9	Supertrophic
Humuhumu	-36.32808333, 174.1294667	11/7/2018	130.3	15	Mesotrophic
Rotootuauturu	-36.33137007, 174.1397831	8/13/2019	16.1	6	Eutrophic
Rotokawau	-36.35028333, 174.1465167	11/7/2018	25.7	13	Mesotrophic

* https://www.lawa.org.nz

[5] Class 1 lakes are shallow dune lakes that lie above the groundwater table and receive water primarily from rainfall and surface run-off.

2.2 Northland Regional Council lake monitoring

The lake has been monitored by NRC since 2005 as part of their existing state of the environment programme (NRC 2022). Discrete measurements of oxygen concentrations and water temperature were collected from Lake Ngatu sporadically from 1996 to 2004 (typically between two and five times per year). Routine quarterly sampling began in 2005, with monthly sampling introduced from 2022 to 2025. In addition, the monitoring used high-frequency data from an actively operating buoy, recorded at 15-minute intervals between 27 September 2022 and 19 February 2025. To provide a more detailed assessment of water temperature and oxygen conditions, we used the 15-minute interval data to assess events of thermal stratification and low oxygen conditions. Both measurements were collected by NRC from near both the surface and the bottom of the lake.

Data on key water quality parameters were obtained from the NRC environmental data hub[6] and the Land, Air, Water Aotearoa (LAWA) data portal.[7] From the available data, we used chlorophyll-*a* (chl-*a*), total phosphorus (TP) and total nitrogen (TN), as these are widely recognised indicators for lake water quality and trophic status.

The LERNZmp lake modelling platform[8] was used to source modelled catchment P and N loads ($t{\cdot}yr^{-1}$). A Vollenweider model was then used to convert these load estimate into in-lake concentrations using the following equation:

$$TP = \frac{L}{V \times p^{-1}}$$

Where *TP* is total P concentration ($g{\cdot}m^{-3}$), *L* is the load ($g{\cdot}yr^{-1}$), *V* is lake volume (m^3) and *p* is the lake residence time (years). A comparison of these modelled TP and TN concentrations with *in situ* measured values provides an indication whether internal nutrient cycling is acting as a net source (measured >> modelled) or sink for nutrients (measured << modelled).

2.3 Sediment geochemistry

Detailed sediment data for Lake Ngatu (including sediment characteristics and 'glove box' experimental results) were obtained from the Lakes380 research programme (Table 2). For the other Northland lakes, sediment data were limited to P fractionation forms determined through sequential analysis.

It is important to note that the sediment samples for Lake Ngatu and other Northland lakes were collected once, from the deepest location in each lake, providing a snapshot in both time and space. However, lake sediment characteristics are integrative and reflect longer-term environmental patterns in comparison to water column assessments (Waters et al. 2023). From each lake, surface sediment (i.e. the top 2 cm) was collected using a 25 cm^2 Ponar grab sampler. Surface sediment samples were analysed for sediment geochemistry, P fractionation forms, and N and P release rates as per Waters et al. (2021).

[6] https://www.nrc.govt.nz/environment/environmental-data/ [accessed 6 May 2025]
[7] https://www.lawa.org.nz [accessed 6 May 2025]
[8] https://limnotrack.shinyapps.io/LERNZmp/ [accessed 23 May 2025]

Sediment characterisation of Lake Ngatu

Sediment density was calculated using a known volume of dry sediment from the top 0–1 cm section of sediment cores collected from the lake as part of the Lakes380 programme. Pore-water volume was determined after centrifugation and decanting of the pore water. Organic matter content was estimated based on the loss on ignition at 550 °C for 4 hours. Carbonate content was calculated using additional loss on ignition at 950 °C for 2 hours.

Sediment samples were sent to Hill Labs for the following analyses: (a) grain size analysis for < 0.63 µm, 0.63 µm–2 mm, and > 2 mm size ranges; (b) sediment bulk density; (c) total recoverable P, iron (Fe), manganese (Mn), calcium (Ca) and aluminium (Al); (d) total organic carbon (TOC); (e) total sediment nitrogen (TSN); and (f) sediment pore water for TP and dissolved reactive phosphorus (DRP).

Phosphorus fractionation for Lake Ngatu and Northland lakes

Different forms of sediment-bound P were analysed at the Cawthron Institute laboratory using a sequential chemical extraction method, based on a modified 'Psenner-type' protocol adapted from Rydin (2000). This method allowed the identification and quantification of the following P fractions used in this report:

Bioavailable / mobile phosphorus fractions

- **Exchangeable phosphorus (Ex-P):** loosely bound and soluble P.
- **Redox-sensitive phosphorus (Red-P):** P that may be mobilised under low oxygen conditions, commonly associated with iron and manganese hydroxide minerals.
- **pH-sensitive phosphorus (pH-P):** P that may be mobilised in high pH conditions.
- **Organic phosphorus (Org-P):** easily degradable organic P.

Refractory phosphorus fractions

- **Residual phosphorus (Res-P):** refractory, non-bioavailable P.
- **Calcium-bound phosphorus (Ca-P):** refractory phosphorus associated with Ca minerals.

Total sedimentary phosphorus (TSP): the sum of all P fractions.

Among these, Ex-P, Red-P, pH-P and Org-P are considered the most mobile and potentially bioavailable forms of P (Waters et al. 2021), while Res-P and Ca-P represent refractory ('non-bioavailable') forms of P.

An anoxia P and N release experiment was conducted in a sealed 'glove box' purged with oxygen-free N gas. Sediment samples in 15 mL tubes were incubated under anoxic and oxic conditions for a 36-hour period. After incubation, the tubes were sealed and centrifuged, and the supernatant was decanted and filtered through 0.45 µm pore-size filters. The filtered solutions were then sent on ice to Analytica Laboratories for TP and TN analysis. Daily (24-hour) release rates were calculated based on the total mass released over the 36-hour incubation period.

It is worth noting that the sequential P analysis results differ from those of the 'glove box' experiment. The sequential analysis indicates the forms of P available in the sediment, while the 'glove box' experiment estimates the maximum potential release of P under anoxic conditions combined with physical disturbance. The 'glove box' data should be considered as a proxy for risk associated with a large-scale disturbance such as a severe tropical storm like ex-tropical Cyclone Gabrielle.

3. Results and discussion

3.1 Water quality

Total nitrogen, total phosphorus and chlorophyll-*a*

The water quality of Lake Ngatu (Figure 3) varied across the data record. TN levels were high throughout the monitoring period (NPS-FM bands C and D; 2005–25 average = 0.9 $g \cdot m^{-3}$) and peaked sharply in 2022 (average = 1.7 $g \cdot m^{-3}$). TP concentrations remained below 0.02 $g \cdot m^{-3}$ for most of the sampling period, except in 2005, 2007, 2008 and 2011, and with the highest value recorded in 2024. Chl-*a* concentrations, a proxy for algal biomass, exceeded the bloom threshold of 20 $\mu g \cdot L^{-1}$ (Waters et al. 2021) once in 2009 (17 August) and 2020 (25 November), and twice in 2015 (9 February and 18 May) and 2022 (21 March and 22 November) (Figure 3C).

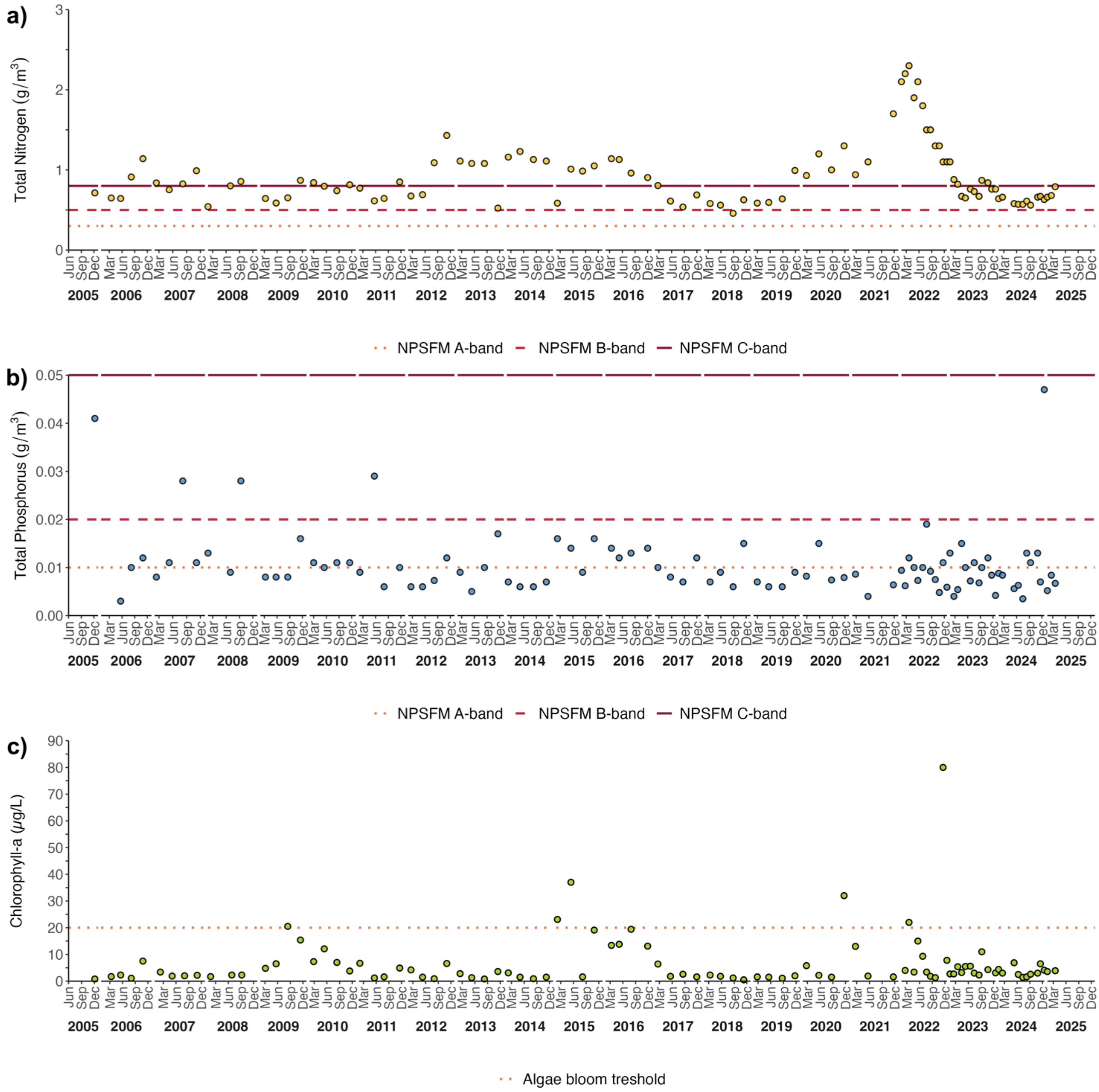

Figure 3. Lake Ngatu surface water quality parameters sampled between 2005 and 2025. (A) Total nitrogen, (B) total phosphorus and (C) chlorophyll-*a*. Total nitrogen frequently exceeded national thresholds during 2020–22, total phosphorus remained mostly below B band levels with few exceedances, and chlorophyll-*a* was generally low with occasional peaks.

Trophic Level Index

In this report, we used TLI4 which combines TP, TN, chl-*a* and Secchi disc depth (water clarity).

The lake TLI showed a stable pattern over the monitoring period with a 3–4 year cycle of increases and decreases between 2009 and 2023. The TLI for Lake Ngatu indicates poor to fair water quality (Figure 4), corresponding to eutrophic and mesotrophic conditions, respectively.

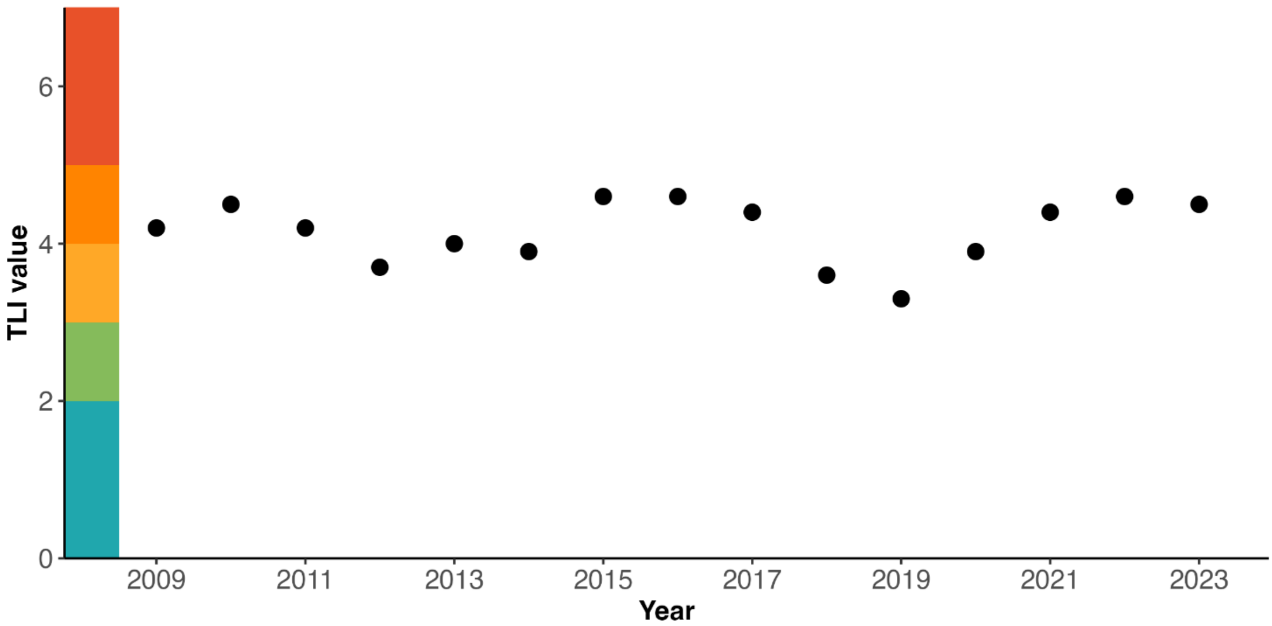

Figure 4. Lake Ngatu Trophic Level Index (TLI4). The coloured bar along the y-axis represents trophic state categories, from 0–2 microtrophic (blue) to 5–7 supertrophic (red). Lake Ngatu fluctuated between mesotrophic (light orange) and eutrophic (dark orange) over the monitoring period.

Water temperature and dissolved oxygen

Temperature

High-frequency data from Lake Ngatu revealed periods of thermal stratification during the spring and summer seasons, characterised by surface water temperatures being more than 1 °C higher (Wetzel 2001) than bottom water temperatures (Figure 5). In contrast, the long-term dataset did not show a clear seasonal pattern, except for general winter–summer differences and in 2022, when monthly data were available (Figure 6). This is likely due to the sporadic nature of sampling in most other years and highlights the importance of high-frequency monitoring in shallow and dynamic lakes.

Dissolved oxygen

The low frequency oxygen monitoring data from 1996 to 2022 showed that dissolved oxygen (DO) concentrations in both surface and bottom waters remained above the National Policy Statement for Freshwater Management 2020 (NPS-FM) bottom line threshold (> 4 $mg \cdot L^{-1}$) (Figure 7). However, continuous oxygen monitoring between 2022 and 2025 recorded at least 11 instances (based on the Figure 8) when the lake bottom DO concentrations fell below the NPS-FM 'risk of nutrient release' threshold (< 2 mg DO·L^{-1} – indicating hypoxic condition).

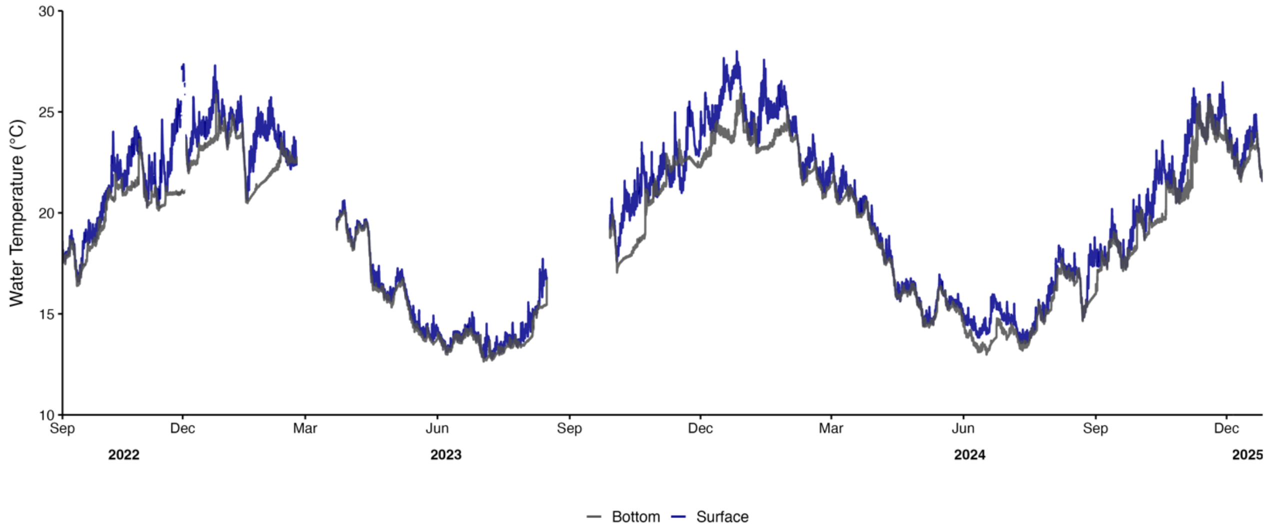

Figure 5. Lake Ngatu high-frequency water temperature data at the surface (epilimnion – dark blue colour) and near the lake bottom (hypolimnion – grey colour). Periods when the two lines diverge indicate thermal stratification and periods when they converge indicate complete water column mixing.

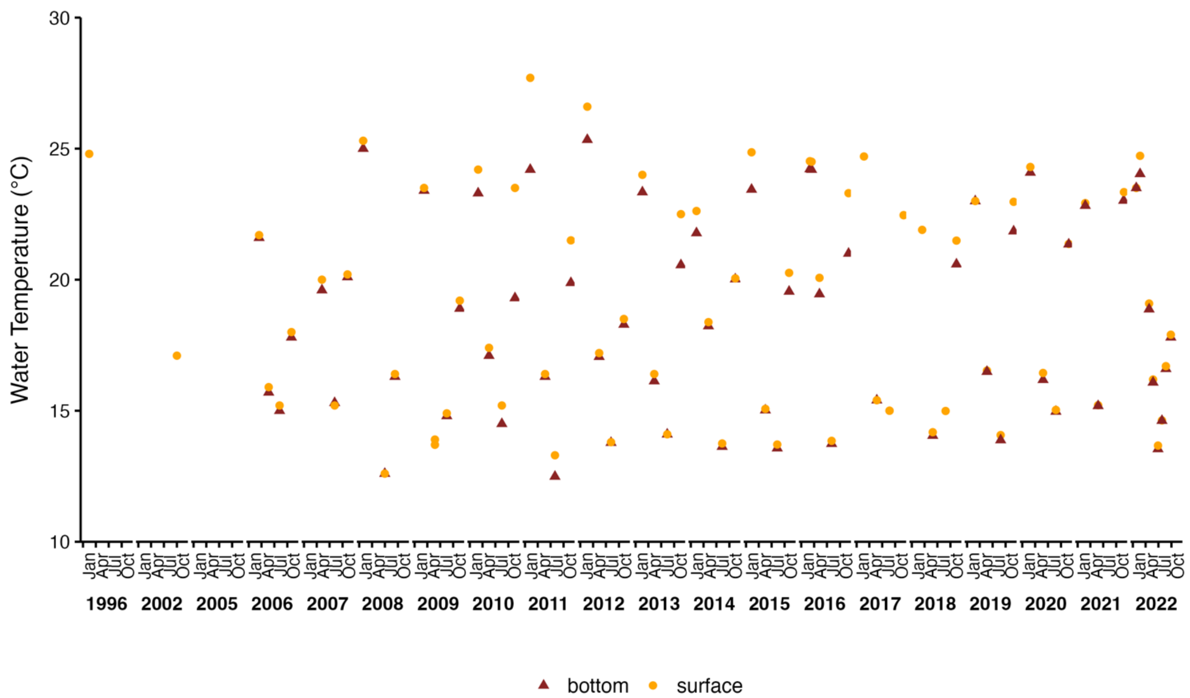

Figure 6. Lake Ngatu long-term discrete records of water temperature at the surface (epilimnion – orange circle) and near the lake bottom (hypolimnion – maroon triangle).

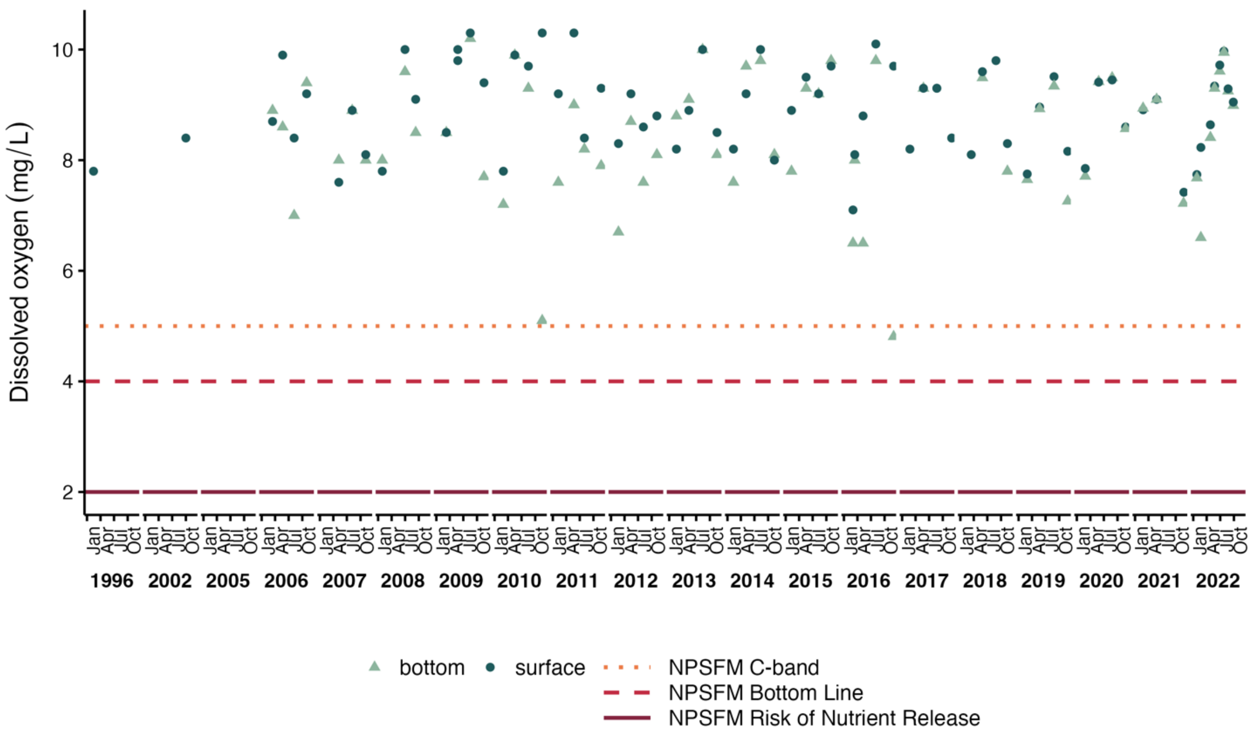

Figure 7. Lake Ngatu discrete dissolved oxygen (DO) concentrations at the surface (epilimnion – dark green dot) and near the lake bottom (hypolimnion – light green triangle). There was no significant trend in either surface (P = 0.2) or bottom water (P = 0.1) DO concentrations over the study period. The NPS-FM bottom line represents the mid-hypolimnetic DO attribute, while the NPS-FM risk of nutrient release line represents the lake-bottom water DO attribute (Zieltjes 2023).

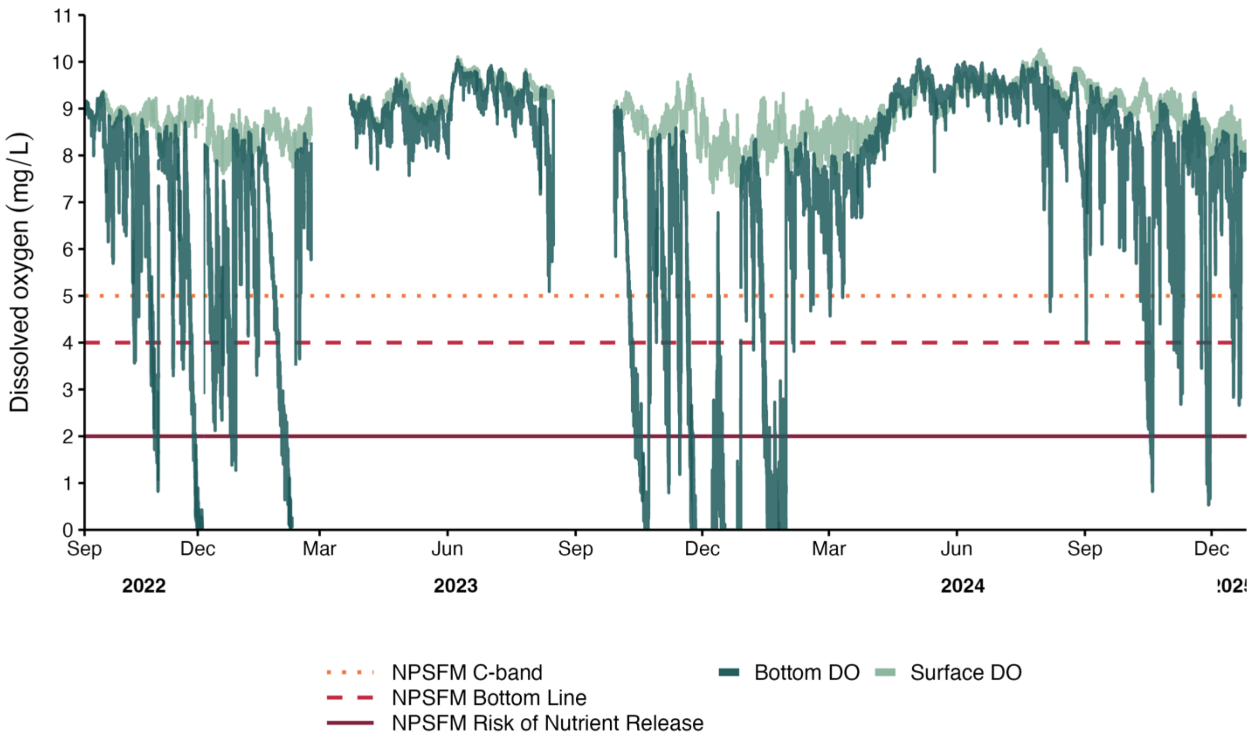

Figure 8. Lake Ngatu dissolved oxygen (DO) concentrations at the surface (epilimnion – light green line) and near the lake bottom (hypolimnion – dark green line). The NPS-FM bottom line represents the mid-hypolimnetic DO attribute, while the NPS-FM risk of nutrient release line represents the lake-bottom water DO attribute (Zieltjes 2023). We used the mid-hypolimnetic criterion as it better reflects the conditions captured by the logger across the lower water column, rather than just at the immediate sediment–water interface, which can be difficult to target consistently due to fluctuations in lake level. The mid-hypolimnetic threshold is also slightly more conservative in identifying anoxic or low-DO events. Given the ecological sensitivity of the lake and the importance of early identification of stress conditions, we opted for a precautionary approach.

We found that as the temperature difference between the surface and bottom layers increased (i.e. the lake stratified), bottom oxygen concentrations declined rapidly (Figure 9). Rates of oxygen depletion were quantified during four periods when the temperature difference remained consistently above 1 °C (Figure 10). The most rapid oxygen decline occurred in the summer of 2022–23, with a rate of $-0.8\ mg\ O_2 \cdot L^{-1} \cdot day^{-1}$. Most continuous depletion events lasted 10–20 days. In January 2023, stratification in Lake Ngatu was disrupted after 11 days, possibly due to wind-induced mixing. While Cyclone Hale (8–12 January 2023) occurred around the same time and could have contributed, the lack of local meteorological data prevents us from confirming this link. Nevertheless, the event highlights that wind-driven mixing may play an important role in influencing bottom-water oxygen levels in Lake Ngatu.

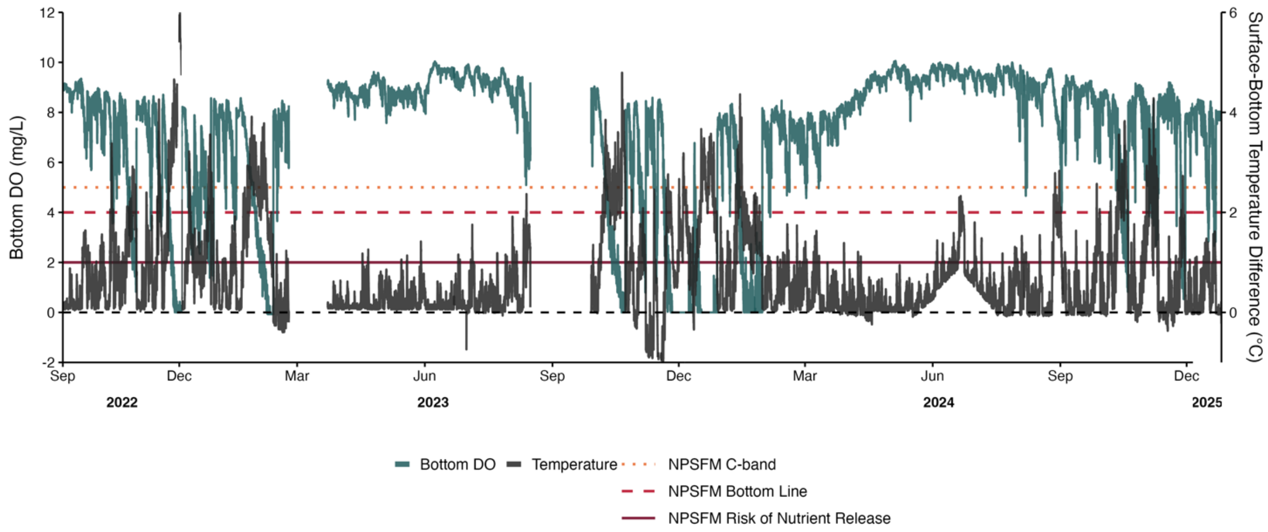

Figure 9. Temperature differences (right y-axis) between surface (epilimnion) and bottom (hypolimnion) waters (black line), and oxygen concentrations (left y-axis) in the bottom (hypolimnion – dark green line) of Lake Ngatu. The 'NPS-FM Bottom Line' represents the mid-hypolimnetic dissolved oxygen (DO) attribute, while the 'NPS-FM Risk of Nutrient Release' line represents the lake-bottom water dissolved oxygen attribute (Zieltjes 2023). Key findings include seasonal stratification (higher surface-bottom temperature differences in warmer months) and hypolimnetic oxygen depletion, particularly in late summer / autumn, indicating potential nutrient release risks when bottom DO falls below the NPS-FM threshold.

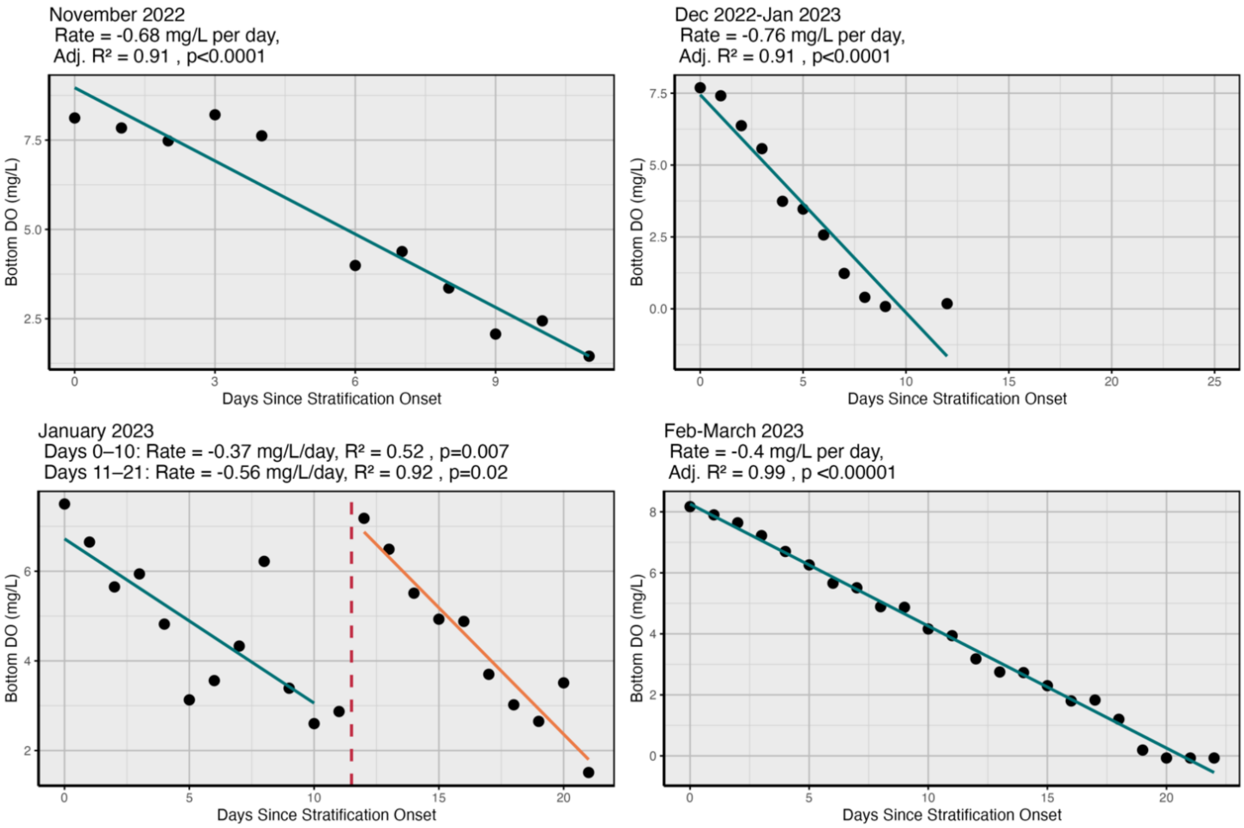

Figure 10. Rates of bottom oxygen depletion in Lake Ngatu under continuous thermal stratification, highlighting extreme variability (from –0.137 mg·L^{-1}·day^{-1} to –0.758 mg·L·day^{-1}) driven by seasonal and event-scale dynamics. The red dashed line represents a wind-induced mixing event (possibly a consequence of Cyclone Hale) in January 2023.

3.2 Lake Ngatu sediment characterisation

Phosphorus fractions

Phosphorus fractionation in the surface sediment of Lake Ngatu (Table 2) revealed that 53.1% of sediment-bound P is in the mobile fraction (Figure 11). The refractory P fraction accounted for 46.9%, indicating that nearly half of the sediment P is not bioavailable. Redox-sensitive (Red-P) and pH-soluble (pH-P) forms were present in low proportions, with only 2.1% potentially released under anoxic conditions and 9.8% soluble under elevated pH conditions (i.e. > pH 9). Exchangeable phosphorus (Ex-P) was particularly low, comprising just 0.6% (6.6 mg P·kg^{-1} dry weight [DW]) of the total sediment P. This contributed to the low total and dissolved P concentrations observed in the pore water above the sediment surface. Together with the low equilibrium P concentration (EPC; 0.004 mg·L^{-1}; see Table 2) and high sediment density (2.8 kg·m^{-2}), these conditions may limit significant P flux to the water column.

Organic P made the largest contribution to the bioavailable and easily accessible sediment P pool, accounting for 40.6%, likely originating from settling phytoplankton, decaying macrophytes or terrestrial vegetation inputs.

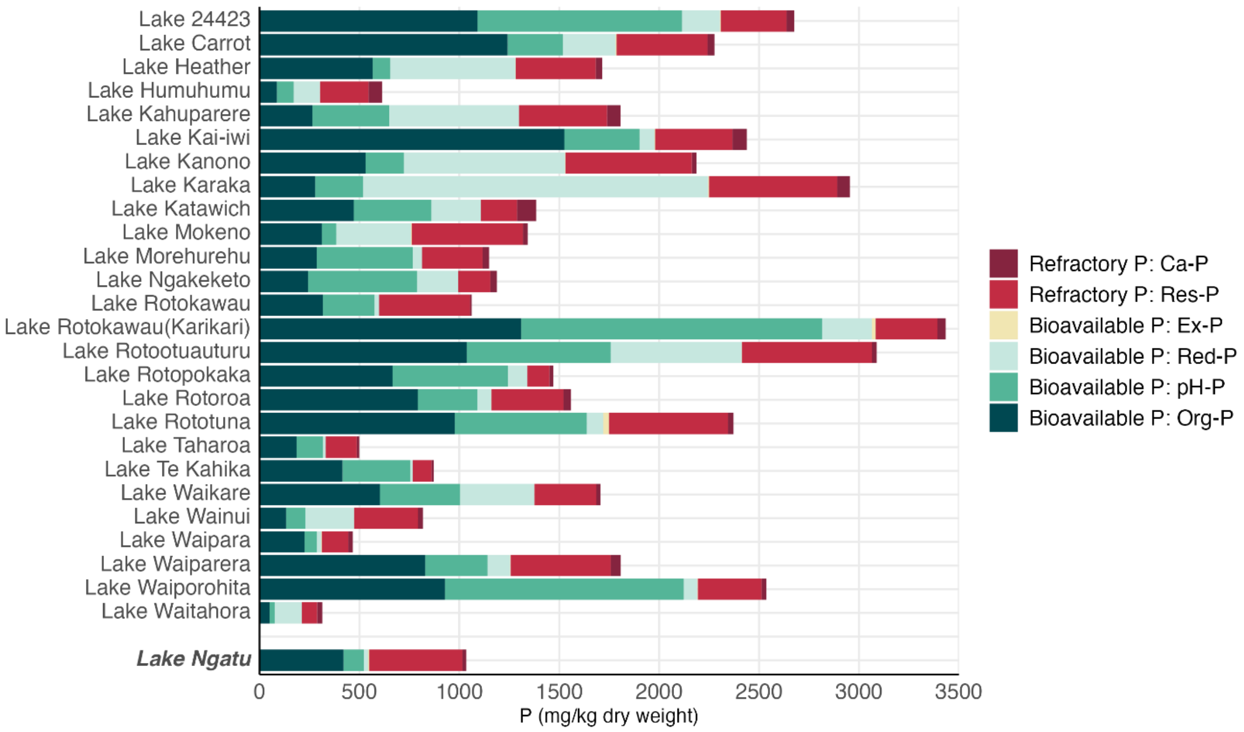

Figure 11. Sediment phosphorus (P) fraction forms in Lake Ngatu and 26 other Northland lakes. Ca-P = calcium-bound P, Res-P = residual P, Ex-P = exchangeable P, Red-P = redox-sensitive P, pH-P = pH-sensitive P, Org-P = organic P.

Comparisons between Lake Ngatu and 26 other Northland lakes

Compared to the 26 other Northland lakes, Lake Ngatu had low sediment concentrations of mobile P forms (Figure 11). TSP for Lake Ngatu (1,034 mg P·kg^{-1} DW) was less than the average value of other Northland lakes (1,682.2 ± 844.5 mg P·kg^{-1} DW). Sediment TN for Lake Ngatu was 1,800 mg·kg^{-1} DW, which was slightly above the average of the other 26 Northland lakes (1,510 ± 920 mg·kg^{-1} DW).

Among the bioavailable P forms, Ex-P in Lake Ngatu was higher (6.6 mg P·kg^{-1} DW) than the average for other lakes (3.5 ± 6.1 mg P·kg^{-1} DW). However, Ex-P still represents a relatively small proportion of the TP content in the sediment for Lake Ngatu (0.6% of total sediment P) and other Northland dune lakes (average = 0.2±0.3% of total sediment P), which suggests low concentrations of readily available P in sediment for those lakes. Other forms of bioavailable P in Lake Ngatu sediments, i.e. Red-P (21.3 mg·kg^{-1} DW), pH-P (101.7 mg·kg^{-1} DW) and Org-P (419.7 mg·kg^{-1} DW), were approximately 13 (288.3 ± 361.8 mg·kg^{-1} DW), 4 (413.1 ± 357.1 mg·kg^{-1} DW) and 1.4 (590.7 ± 406.7 mg·kg^{-1} DW) times lower, respectively, than the mean for the other Northland lakes. This suggests that Lake Ngatu, on average, has a low amount of sediment bioavailable P compared to similar dune lakes in the Northland Region.

Total metal concentrations in Lake Ngatu sediments – such as iron (Fe; 14,700 mg·kg^{-1} DW), manganese (Mn; 76.7 mg·kg^{-1} DW) and calcium (Ca; 5,060 mg·kg^{-1} DW) – were generally below the median values observed in the other Northland lakes. However, Al (32,900 mg·kg^{-1} DW) was nearly twice as high as the average for the other lakes (18,945 $mg \cdot kg^{-1}$ DW). The elevated Al concentration in Lake Ngatu sediments is noteworthy due to its potential to bind, sequester and bury P, limiting its release into the water column. In freshwater systems, Al-bound P is generally considered stable, even under anoxic conditions, because Al does not undergo redox transformations like Fe or Mn. For P to be released from Al-bound forms, conditions such as low pH (< 4–5), high levels of dissolved organic matter, or sediment resuspension (e.g. from wind, waves or fish activity) are typically required (Wang et al. 2009; Huser et al. 2016).

The indication that sediments in Lake Ngatu are acting as a substantial P sink is supported by the comparison of modelled and measured TP concentrations. Modelled TP (5-year average = 0.020 $g \cdot m^{-3}$) was substantially higher than measured TP (5-year average = 0.008 $g \cdot m^{-3}$), indicating that the sediment is sequestering approximately 60% of the catchment nutrient load. By contrast for N, modelled TN (0.119 $g \cdot m^{-3}$) was substantially lower than measured TN (average = 1.100 $g \cdot m^{-3}$). This discrepancy may indicate that there are sources of N that are unaccounted for within the catchment, such as septic tanks; however, it is more likely that the catchment soil has a lower-than-average assimilative capacity for absorbing N inputs derived from intensive farming.

Table 2. Analysis of Lake Ngatu sediment samples (top 0–2 cm), including sediment chemistry, phosphorus geochemistry from the Lakes380 dataset, and nutrient release experiments. DW = dry weight.

Parameter		Unit	Value
Sediment characterisation			
Total sedimentary phosphorus		mg·kg^{-1} DW	1,035
Total sedimentary nitrogen		mg·kg^{-1} DW	1,800
Bulk density		kg·m^{-2} DW	2.8
Organic matter		%	45.6
Carbonate content		%	5.3
Grain size	< 0.63 µm	% DW	22.9
	0.63 µm to 2 mm	% DW	75.8
	> 2 mm	% DW	1.3
Total organic carbon		% DW	17.1
Total metals	Iron (Fe)	Light table entry	14,700
	Manganese (Mn)	mg·kg^{-1} DW	76.7
	Aluminium (Al)	mg·kg^{-1} DW	32,900
	Calcium (Ca)	mg·kg^{-1} DW	5,060
Pore water			
Total dissolved phosphorus		mg·L^{-1}	0.8
Dissolved reactive phosphorus		mg·L^{-1}	0.3
Phosphorus fractionation			
Exchangeable phosphorus		mg·kg^{-1} DW	6.6
Redox-sensitive phosphorus		mg·kg^{-1} DW	21.3
pH-sensitive phosphorus		mg·kg^{-1} DW	101.7
Organic phosphorus		mg·kg^{-1} DW	419.7
Calcium-bound phosphorus		mg·kg^{-1} DW	20.4
Residual phosphorus		mg·kg^{-1} DW	465
Nutrient release experiments ('glove box')			
Equilibrium phosphorus concentration		mg L^{-1}	0.004
Anoxic release phosphorus		mg kg^{-1} DW day^{-1}	37.8
Areal anoxic release phosphorus		mg m^{-2} day^{-1}	105.9
Anoxic release nitrogen		mg kg^{-1} DW day^{-1}	64.5
Areal anoxic release nitrogen		mg m^{-2} day^{-1}	180.9

Phosphorus mass release rates from the 'glove box' experiment

Results of the 'glove box' experiment on P mass release rates in Lake Ngatu sediment indicate that under anoxic conditions, the release rate was 37.8 mg P·kg^{-1}·day^{-1} (Table 2). Compared to other dune lakes in Northland, Lake Ngatu shows a moderate potential for P release under anoxic conditions. Buoy monitoring data on oxygen conditions in Lake Ngatu from 2022 to 2025 indicate that bottom waters became anoxic (0 mg DO·L^{-1}) on at least 11 occasions (Figure 8). However, these anoxic events were short-lived, typically lasting only a few (3–5) days. The longest period of anoxia occurred in summer (December–January) 2023–24, when oxygen concentrations remained at zero for 16 days. These findings indicate that while internal P recycling from Lake Ngatu sediments is possible, it would likely require prolonged anoxic conditions and / or physical disturbance of the sediments to become significant.

The areal anoxic P release rate based on the 'glove box' experiment was 105.9 $mg \cdot m^{-2} \cdot d^{-1}$, which is approximately three times higher than the average areal release rate observed in the other Northland dune lakes (37.5 ± 64.4 $mg \cdot m^{-2} \cdot d^{-1}$).

Caution should be exercised when interpreting this value, as the analysis was conducted on 'slurries' rather than under *in situ* conditions using intact sediment cores. The glove box experiment likely overestimates actual release rates (by area and by mass), which in natural settings are constrained by slower, diffusion-driven processes at the sediment–water interface (Wetzel 2001).

Nitrogen release in Lake Ngatu was also calculated, with a rate of 180.9 $mg \cdot m^{-2} \cdot d^{-1}$. In comparison, the median TN release rate in the other Northland lakes was 212 ± 250.9 $mg \cdot m^{-2} \cdot d^{-1}$. In conclusion, N release in Lake Ngatu was nearly twice that of P, but still considerably lower than the stoichiometric requirements for algal growth. This indicates that P availability from sediments is the primary limiting factor for productivity, and N release is likely a minor contributor to the overall risk of algal blooms in the lake.

Despite the relatively high P release rates observed in the 'glove box' experiment (105.9 $mg \cdot m^{-2} \cdot d^{-1}$ by area and 37.8 $mg \cdot kg^{-1} \cdot day^{-1}$ by weight) these values are considered within a worst-case scenario for maximum P release. While they are higher than the average values for other Northland lakes (37.5 ± 64.4 $mg \cdot m^{-2} \cdot d^{-1}$ and 20.9 ± 35.2 $mg \cdot kg^{-1} \cdot day^{-1}$, respectively), multiple lines of evidence suggest that sediments in Lake Ngatu act more as a nutrient sink than a source**.** This includes evidence from sediment density, EPC and total metal concentrations (particularly Al), and comparisons between modelled and measured concentrations in Lake Ngatu.

4. Conclusions and recommendations

Knowledge of internal nutrient loading is an important component of lake management strategies aimed at maintaining lake health or preventing its deterioration. Shallow lakes with no outflow are especially prone to poor water quality due to the release of P from sediments (Cooke et al. 2005; Schindler 2012). Depending on the system, internal loading can remain a significant issue for decades (Jeppesen et al. 2005; Kangur et al. 2013). Numerous studies have demonstrated that controlling P is essential for mitigating eutrophication and restoring lake ecosystems (Carpenter 2008; Schindler 2012). Therefore, identifying the primary sources and processes responsible for P release from lake sediments into the water column is a crucial step before considering remediation options.

The analysis of Lake Ngatu sediment quality showed that more than 50% of the P pool is considered bioavailable and potentially can be recycled into the water column under specific conditions. These conditions can include microbial mineralisation of organic P, anoxic conditions, changes in pH and sediment resuspension. Based on the buoy oxygen data, we found that anoxic conditions are common in Lake Ngatu during the summer months. The anoxic conditions near the lake bottom may lead to low pH (e.g. < 4–5) and further release of P, but additional data (pH continuous measurements at the bottom waters) would be required to confirm this assumption; these data could be collected during future monitoring of the lake.

Sediment characteristics in Lake Ngatu indicate a low potential for P release under natural conditions. Oxygen- and pH-sensitive P fractions (Red-P and pH-P) were found to be low, despite high P release rates observed under laboratory conditions (i.e. 'glove box' experiment). In addition to the low Red-P and pH-P fractions, the exchangeable P (Ex-P), pore-water P concentrations (both TP and DRP), and equilibrium P concentrations (EPC) were also low. Additionally, sediment data showed high concentrations of aluminium (Al), which plays a key role in stabilising P in sediments and contributes to its long-term storage and biogeochemical cycling. Compared to Al, manganese (Mn) and iron (Fe) bind with P under oxic conditions but are more prone to releasing P under anoxic conditions. In contrast, Al forms more stable and less reversible complexes with P, further limiting its release. These findings, combined with relatively high sediment density (which reduces the likelihood of wind-induced resuspension) (Li et al. 2017), suggest a limited risk of internal P loading from Lake Ngatu sediment. Overall, the above evidence indicates that the sediment currently acts more as a sink than a source of P. While comparisons between modelled and observed nutrient concentrations in Lake Ngatu support the evidence that internal cycling acts as a sink for catchment-derived P, there appears to be a substantial source of unaccounted nitrogen (N). In-lake total nitrogen (TN) concentrations have increased substantially over the last decade, coinciding with algal bloom events, and further work should investigate this issue.

One of the main bioavailable forms of P in Lake Ngatu sediments was organic P (Org-P), comprising more than 40% of the total sediment P pool. The high Org-P concentration is likely a result of elevated in-lake primary production or external loading from the surrounding watershed. High fluxes of organic material into lake sediments have been shown to increase oxygen demand (Chen et al. 2012) or enhance the mineralisation of organic matter (Hupfer and Lewandowski 2008), both of which can lead to direct P release into the water column. Therefore, Org-P levels are expected to remain high as long as elevated primary productivity persists in the lake (Waters et al. 2021).

There is still some uncertainty about the role of sediment nutrient processes in shaping water quality conditions in Lake Ngatu. For example, previous reports (Kuczynski et al. 2024; Hughes 2016) have suggested that both internal and external P loadings may contribute to P release under conditions of low dissolved oxygen and high pH. In contrast, the findings of this report indicate that sediment in Lake Ngatu currently acts as a P sink. This difference in interpretation reflects the use of different lines of evidence – sediment chemistry and stability data in the current study versus water quality trends and catchment correlations in earlier reports. To resolve these different perspectives and address the remaining gaps, further investigation is needed to better quantify both internal and external nutrient loading dynamics. Given the risk of P release observed in sediment data from the other Northland lakes, Lake Ngatu offers strong potential as a representative case study for future nutrient budget modelling across the region's dune lakes. Thus, we recommend maintaining a focused effort on Lake Ngatu as a model system, and propose the following actions:

- Develop a water balance model for Lake Ngatu that includes surface water and groundwater components (e.g. inflows, connectivity between surface and groundwater, precipitation and lake level data).
- Quantify nutrient loads from the lake catchment, with particular attention to contributions from stormwater and nearby wastewater sources.
- Continue high-resolution monitoring of dissolved oxygen and temperature, and expand measurements to include pH and conductivity near the lake bottom. Consider deploying additional sensors throughout the water column to improve the resolution of thermal profiles and enable more accurate calculation of thermocline depth.
- Deploy sediment traps to estimate sedimentation rates in the lake; these will help inform the nutrient budget and improve understanding of organic matter loading and burial rates.
- Assess macrophyte cover and biomass, and investigate the mechanisms by which phytoplankton stress may contribute to macrophyte collapse.
- Determine the nutrient content of macrophytes to assess the potential nutrient release associated with macrophyte die-off events.
- Develop a wind stress model to evaluate the wind energy required to fully mix the lake water column from bottom to surface. This will improve understanding of how wind-driven mixing events influence internal nutrient release.

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