

Benthic Nutrient Release from Auckland Dune Lakes



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By Grant Tempero and Deniz Özkundakci
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Environmental Research Institute – Te Tumu Whakaora Taiao
Division of STEM
University of Waikato, Private Bag 3105
Hamilton 3240, New Zealand

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Cover image: Lake Whatihua, located west of Waiuku in the Auckland region.

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Reviewed by:



Matthew Prentice
Research Fellow
University of Waikato

Approved for release by:



Charles Lee
Director
Environmental Research Institute

Executive Summary

New Zealand’s freshwater lakes are under pressure from land use intensification, discharge of nutrient contaminants and over-allocation of groundwater resources. Dune lakes are comparatively rare ecosystems formed by wind-blown sand which creates depressions or water impoundments. Often isolated and diversity depauperate, their geomorphological features can make them particularly vulnerable to anthropogenic eutrophication. Ecological models provide a tool for assessing potential strategies for remediation of lake eutrophication. However, they require an understanding of the drivers of water quality decline, including external and internal nutrient loading. The University of Waikato was contracted by Auckland Council to assess lake littoral groundwater infiltration rates and sediment nutrient release rates in seven dune lakes to support the development of ecological models for the lakes.

Littoral groundwater infiltration was measured using custom moulded clear acrylic domes fitted with valves which allowed water passage into an attached collection bag. The chambers were deployed in the winter and of late spring of 2023. Depending on lake size and site suitability, between one and four chambers were deployed in the littoral zone (generally ~0.5m depth) of each lake and left in place for 24 hours. Net groundwater efflux was not detected by any of the chambers, while groundwater infiltration rates ranged from 1.0–7.4 L m⁻² day⁻¹. Assessment of groundwater nutrient concentrations was not feasible due to the volume of the chamber (16 L) and the deployment period required to determine infiltration rates. Littoral groundwater infiltration likely constitutes a significant proportion of the inflow to these lakes, and rates appear to be volumetrically proportional to the linear distance to the catchment boundary from the point of sampling, and to variance in catchment rainfall. Littoral infiltration rates responded quickly (<24 hours) to total precipitation preceding sampling; however, this may be partially due to the higher-than-average rainfall and soil saturation during the 2023 survey period.

Winter and spring littoral groundwater infiltration rates for seven Auckland dune lakes.

	No. of chambers	Lake littoral infiltration rate (L m ⁻² day ⁻¹)				
		Winter		Spring		Annual
		Mean	Range	Mean	Range	Mean
Kawaupaku	1	1.0	1.0	N/D	–	1.0
Ōkaihau	3	N/D*	–	3.2	2.0–4.6	3.2
Te Kanae	3	2.3	1.5–5.5	3.7	3.2–4.2	3.0
Whatihua	3	3.3	2.2–4.1	5.3	4.2–7.2	4.3
Slipper	1	1.0	1.0	7.8	7.8	4.4
Spectacle	2	4.0	3.7–4.2	3.3	2.2–4.3	3.6
Tomarata	4	3.8	1.7–5.4	5.3	3.7–4.6	4.6

*Site was not accessible.

Sediment nutrient release rates were determined using benthic incubation chambers deployed at or near the deepest point of each lake during the spring of 2023. Four dark chambers were deployed in each lake for between 32–68 hours, water samples were pumped from each chamber and analysed for dissolved nutrients. Lakes Kawaupaku, Ōkaihau, Te Kanae and Whatihua were strongly stratified with anoxic bottom waters and sediment nutrient release rates could not be determined. Bottom water samples taken at the time of chamber deployment in these lakes found ammonium and nitrate concentrations were high ($>0.2 \text{ mg N L}^{-1}$) but dissolved reactive phosphorus (DRP) concentrations were near or below detection limits ($<0.004 \text{ mg P L}^{-1}$); indicating that internal lake phosphorus loading was likely limited in comparison to nitrogen loading.

The shallow, polymictic nature of the Tomarata, Spectacle and Slipper lakes provided more suitable conditions for determination of in situ sediment nutrient fluxes, although a second deployment in Lake Tomarata was conducted in August 2024. The measured nutrient flux rates, maximum nutrient flux rates and half saturation constants for ammonium and dissolved reactive phosphorus are presented in the table below. The low phosphorus release rates may be due to low external phosphorus loading, associated with episodic sediment loading from the mostly ephemeral surface inflows to the lakes. These findings align with previous work carried out in Lake Tomarata demonstrating the sedimental total phosphorus (TP) pool to have a low redox sensitive phosphorus fraction despite sediment iron content being reasonably high (Waters, 2022).

Sediment dissolved reactive phosphorus (DRP) and ammonium flux rates, maximum nutrient flux rate at 20°C ($S_{(g)}$) and half saturation constant for oxygen (K_{SOD}) for lakes Tomarata, Spectacle and Slipper.

Lake	Nutrient	Measured flux rate ($\text{mg m}^{-2} \text{ day}^{-1}$)	$S_{(g)}$ ($\text{mg m}^{-2} \text{ day}^{-1}$)	K_{SOD}
Lake Tomarata				
	DRP	-	-	-
	Ammonium	1.26	1.97	5.5
Slipper Lake				
	DRP	1.10	1.41	7.0
	Ammonium	4.84	6.47	4.4
Spectacle Lake				
	DRP	1.16	1.59	7.1
	Ammonium	2.73	3.64	8.5

Prolonged stratification of lakes Kawaupaku, Ōkaihau, Te Kanae and Whatihua provided limited opportunity to directly assess internal nutrient loading. However, external phosphorus loading to these lakes is likely to be constrained as they are primarily groundwater fed with small, ephemeral surface inflows. In addition, hypolimnetic DRP concentrations and sediment phosphorus release rates determined for lakes Tomarata, Slipper and Spectacle indicate that internal phosphorus loading is low compared to other New Zealand lakes. External nitrogen loading is likely to be more substantial than phosphorus loading, but internal loading also appears to be lower than average. These findings

underscore the distinct processes driving nitrogen and phosphorus loading, and consequently nutrient concentrations in the lakes studied. They also provide data critical for the parameterisation of subsequent water quality models, which might be used to inform land use practices through comprehensive scenario testing of various management options.

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Introduction

Groundwater Flux

Accurate accounting and knowledge of groundwater dynamics is critical for effective water quality management, particularly in groundwater-dominated catchments (Hamilton et al. (2018). Lakes interact with groundwater either by receiving from or losing water to (i.e., efflux) groundwater across the entire lakebed, or more commonly, over different areas of the lakebed. In a geologically homogeneous setting, groundwater inflow is concentrated in the littoral zone due to the greater occurrence of low-permeability organic rich sediment (Verhagen et al. 2022). Under certain water table and geological conditions both recharge and discharge areas can occur within a lake (Dingman 2015). The flow of groundwater into and out of lakes can have a substantial impact on their hydrologic and nutrient budgets. One of the essential pieces of information required for quantifying a lake hydrologic budget is the groundwater flux. Typically, this is estimated as the residual of surface inflows, precipitation, evaporation and outflow from the lake; however, this requires accurate gauging of surface inflows and discharges (Mitchell et al. 1988). Seepage chambers can provide direct measurement of the water flux across the groundwater–surface water interface at single or multiple points. Bag-type seepage chambers consist of a bottomless chamber vented to a plastic bag. The chamber is inserted into the sediment, and the meter can measure water flux in either direction. To measure groundwater discharge, a deflated plastic bag is used to collect water as it flows from the groundwater to the surface water. To measure surface water discharge to groundwater, a known volume of water is filled into the bag prior to installation, and the net volume loss is calculated (Verhagen et al. 2022). Gibbs et al. (2005) measured seepage rates of groundwater inflow in Lake Taupō’s Whangamata and Whakaipo Bays using seepage chambers at depths up to 6.5 m below lake level. The seepage chambers were located on the lakebed, where cold water was interpreted as groundwater influx, as previously detected by scuba divers.

Nutrient loading

Anthropogenic eutrophication of freshwater ecosystems is of increasing concern to the public and New Zealand governmental agencies, with 46% of New Zealand’s lakes larger than 1 ha in poor or very poor health (Ministry for the Environment 2023). When undertaking remediation of eutrophic lakes, it is generally recommended that both internal and external sources of nutrient loading should be considered through policy and active management (Hamilton et al. 2018). External nutrient loading occurs when nutrients such as phosphorus and nitrogen enter the aquatic environment from point and diffuse discharges from the surrounding catchment (Chislock et al. 2013). Excessive nutrient loading from the catchment often results in oxygen depletion of the hypolimnion due to oxic microbial respiration mediated through the decomposition of sedimented algal blooms (Søndergaard et al. 2001).

Internal nutrient loading primarily occurs through the release of nutrients by microbial decomposition and the redox-dependent release of iron-bound phosphorus from the resulting hypoxia at the interface between the bottom sediment and the water column (Søndergaard et al. 2001). Following stratification breakdown, nutrients which have accumulated in the hypolimnion are mixed into the surface waters making them available for uptake, contributing to the formation of harmful algal blooms and resulting in the loss of recreational amenities (Chislock et al. 2013; Hamilton et al. 2018; Ministry for the Environment 2023).

Internal nutrient loading may comprise a significant proportion of a lake's total nutrient budget, particularly in lakes which have undergone prolonged periods of cultural eutrophication. Phosphorus released from the bottom sediment of shallow lakes can constitute a substantial part of the total loading and may even exceed seasonally external phosphorus loading (Søndergaard et al. 2001). In Mona Lake (Michigan, USA), internal (TP) loads contributed ~9% of the overall phosphorus load in spring, but ~68–82% of the overall phosphorus load in the summer and early autumn (Steinman et al. 2009). Burger et al. (2007) reported dissolved reactive phosphorus (DRP) sediment release rates for Lake Rotorua of between 2.2 to 85.6 mg P m⁻² day⁻¹, depending on depth and season. This indicated that the mean internal release rate of Lake Rotorua was at least three times greater than the mean daily external load for the same period (Burger et al. 2007). In addition to phosphorus, nitrogen release from bottom sediments occurs predominantly as ammonium, as particulate organic matter is mineralised by bacterial decomposition (Forsberg 1989). Autolysis or hydrolysis of organic material can also lead to production of dissolved organic nitrogen, which may be further mineralised to ammonium via bacterial deamination (Hargreaves 1998). Determination of anoxic nutrient release from lake sediments can be critical for the development of lake ecosystem models, as nutrient release rates calculated from water column nutrient mass balance budgets can significantly underestimate internal nutrient loading (Nürnberg 1984).

In addition to the mass balance approach, laboratory-based incubations of sediment cores can provide estimates of DRP and ammonium release rates while allowing parameters such as light and temperature to be regulated (Miller-Way and Twilley 1996). The drawback is that retrieval of the sediment cores may also result in disturbance of flocculated material in the sediment surface layer, disturbance of gas pockets and changes in hydrostatic pressure producing nutrient flux estimates that do not reflect in situ conditions. In comparison, benthic incubation chambers function in situ, and potentially provide a more accurate estimate of nutrient fluxes, as the estimates include the effects of diffusion and the active exchange of nutrients between the sediment and water column by burrowing and irrigating benthic invertebrates (bioturbation) (Nicholson et al. 1999; Hall et al. 2007). Benthic incubation chambers have been extensively employed to examine sediment oxygen and nutrient fluxes in New Zealand coastal marine systems (Jones et al. 2011; Mangan et al. 2022; Thomas et al.

2022) and river ecosystems (Hickey 1988; O'Brian et al. 2012; Quinn et al. 2020), but have only limited application in lake ecosystems, such as Lake Rotorua (Burger et al. 2005). Deployment of benthic incubation chambers allows determination of sediment nutrient fluxes in response to declining dissolved oxygen concentrations, which can then be used to improve lake ecosystem models.

Auckland Council contracted the University of Waikato to determine lake littoral groundwater infiltration rates and sediment nutrient fluxes for eight dune lakes in the Auckland Region. Littoral groundwater chambers were used to determine groundwater infiltration rates on two occasions and benthic incubation chambers were employed to measure sediment nutrient flux rates. This information will assist in the development of water quality models which can be used to inform land use practices and to explore the effects of different scenarios for lake restoration.

Methods

Study Sites

Eight lakes were initially selected as part of the study including Whatihua, Kawaupaku, Okaihau, Te Kanae, Spectacle, Slipper, Tomarata, and Wainamu (Figure 1). However, an intensive storm event on 27 January 2023 followed by further heavy rainfall from Cyclone Gabrielle a fortnight later raised lake water levels and prevented access to Lake Wainamu, which was subsequently omitted from the study. The remaining lakes are all dune lakes which formed between 12,000 (Tomarata, Slipper, Spectacle) and 5,000 years ago (Whatihua, Kawaupaku, Okaihau, Te Kanae) (Lowe and Green 1987; Lowe and Green 1992). At the time of sampling, lake levels were elevated by 1–1.5 m over normal due to the heavy rainfall events at the start of the year.

Lake Whatihua (Figure 2) is located to the west of Waiuku on the southern edge of the Auckland regional boundary, it has a maximum depth of 11 m, a catchment area of 106 ha, and a surface area of 3.9 ha. The catchment is primarily pastoral with small (<1 ha) areas of mature pine and planted native vegetation. Water quality was assessed as mesotrophic in 2017–2019 but appears to have further degraded with persistent algal blooms now occurring (Duggan and Hussain 2021; Groom 2021). The lake is primarily groundwater fed with a single ephemeral surface inflow to the west and no surface outflow.

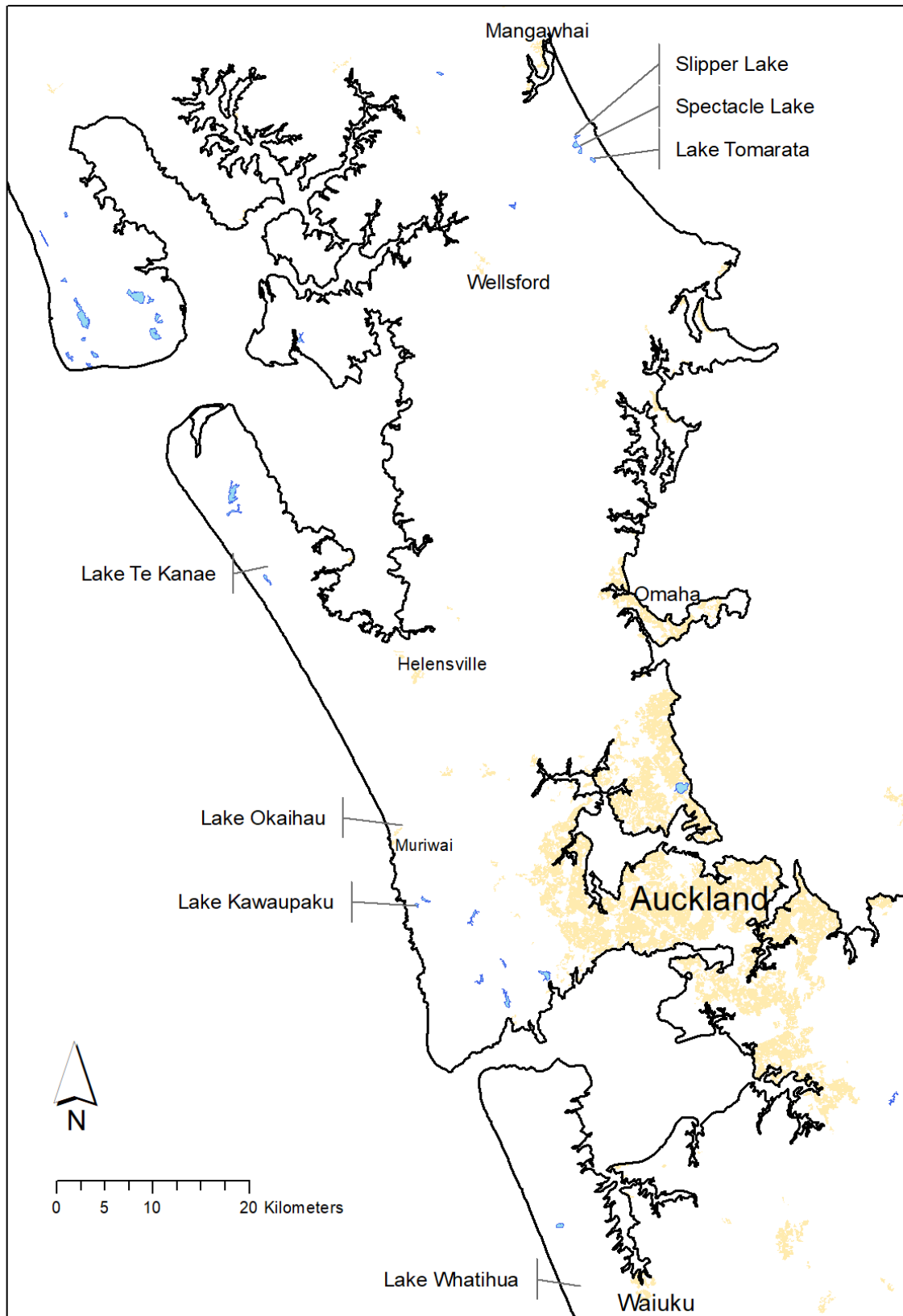


Figure 1. Littoral groundwater infiltration and sediment nutrient release rates were determined for seven dune lakes (Slipper, Spectacle, Tomarata, Te Kanae, Okaihau, Kawaupaku and Whatihua) in the Auckland region.



Figure 2. Lake Whatihua, the catchment is almost entirely pastoral with small areas of planted native vegetation (right of centre).

Lake Kawaupaku (Figure 3) is located on private property in a regenerating forest catchment near Te Henga (Bethels Beach). It has a catchment area of approximately 102 ha, a lake surface area of 9.8 ha, with a maximum depth of 22 m. Inflow is primarily through catchment surface runoff, with a single permanent inflow at the southern end of the lake. The lake is drained by the Taimana Stream on the north side of the lake. Anecdotally, lake water quality has been variable, with a notable decline in submerged macrophyte abundance from 1971 to 2004 and increasing frequency of algal blooms (Barnes 2008). Auckland Regional Council monitoring data (2022-2023) indicates that the lake is eutrophic with a mean TLI of 4.7.



Figure 3. Lake Kawaupaku has a native forest catchment near Bethel's Beach.

Lake Ōkaihau (Figure 4) is located on private property near Muriwai on Auckland’s west coast. The catchment (100 ha) is a mixture of pastoral (27.5%), native (15.6%) and exotic forest (50.7%). The lake covers approximately 5.7 ha, with a maximum depth of 12.8 m; it is fed by a single inflow entering at the southern end of the lake and presumably drains by way of groundwater as there are no surface outflows. A survey of 26 coastal dune lakes in the summers of 1949-1950 by Cunningham et al. (1953) found Lake Ōkaihau to be the only thermally stratified lake with anoxia of the hypolimnion. More recently, a LakeSPI survey found the lake to be in relatively poor condition with invasive macrophyte (*Egeria densa*, *Nymphaea* sp., *Ceratophyllum demersum*) and fish species (*Scardinius erythrophthalmus*) prevalent (de Winton and Edwards 2009), and a TLI of 4.3 indicating the lake is eutrophic.



Figure 4. Lake Ōkaihau, the catchment is a mixture of pastoral, native and exotic forest. Insert: Lake Ōkaihau is fringed by extensive waterlily (*Nymphaea*) beds.

Lake Te Kanae (Figure 5) is located on private property north of Helensville, on the Te Korowai-o-Te-Tonga (South head) peninsula. The lake covers 5.6 ha, with a maximum depth of 23 m. The catchment (42 ha) is vegetated with regenerating bush but is steep sided with evidence of recent large landslips. Water quality is only intermittently monitored but the 2022–2023 TLI indicates that it is eutrophic and likely impacted by recent landslips (ARC monitoring data). In addition, several invasive fish and aquatic plants have been introduced to the lake including koi carp (*Cyprinus rubrofasciatus*), rudd (*Scardinius erythrophthalmus*) and tench (*Tinca tinca*) and hornwort (*Ceratophyllum demersum*) have been introduced to the lake (de Winton and Edwards 2009).



Figure 5. Lake Te Kanae located in a forested catchment on the Te Korowai-o-Te-Tonga (South head) peninsula.

Spectacle Lake (Figure 6) is the largest (43.8 ha) of three dune lakes within the Ngāroto lakes complex south of Mangawhai. Located in an extensively pastoral (80%) catchment (500 ha), the lake is shallow (maximum depth 5 m), devegetated, and has a limited riparian margin. Water quality deteriorated substantially between 1992 and 2005 with the lake classified as hypertrophic (Barnes and Burns 2005). More recent monitoring indicates some improvement in water quality with a mean TLI for 2022-2023 period of 5.9 (supertrophic). Spectacle lake has a single drainage canal which flows into nearby Slipper Lake.



Figure 6. Spectacle Lake is bounded by wetlands to the south and east, but the catchment land use is predominately pastoral.

Slipper Lake (Figure 7) is the smallest of the three Ngāroto Lakes complex with a surface area of 9 ha and a maximum depth of 5.1 m. LakeSPI surveys reported the lake as being devegetated in 1988 and 2008 surveys which they attributed to poor water quality (de Winton and Edwards 2009). The lake is currently classified as supertrophic with a mean TLI for 2022-2023 of 5.6.



Figure 7. Slipper Lake receives inflow from Spectacle Lake via a drainage channel.

Lake Tomarata (15 ha) (Figure 8) is bounded by wetlands to the west and south which contribute to the humic water colouration. The catchment (95 ha) is a mixture of pastoral (45%), wetland (22%) and exotic forest (17.5%). The lake is shallow, with a maximum depth of 5 m and is currently classified as eutrophic (TLI 4.7), with water quality declining markedly following the collapse of submerged vegetation in 2017 (Groom 2021). Lake inflow is primarily through groundwater inflow with some ephemeral overland inflow through the bounding wetlands.



Figure 8. Lake Tomarata is the most southerly of the Ngāroto Lakes and is publicly accessible for recreational activities.

Littoral Groundwater Infiltration

Littoral groundwater infiltration rates for all lakes were measured in the winter (June–August) and spring (October–November) of 2023, apart from Lake Okaihau which could not be accessed in the winter due to saturated ground conditions. Between one and four infiltration chambers were deployed at each lake depending on lake size and site suitability. For deployment, the infiltration chambers required vegetation free substrate in approximately 0.5 m depth at the lake shore. Lake water levels were exceptionally high over in the winter of 2023 due to the previous summer’s intensive rainfall events, this reduced the number of suitable deployment locations, particularly in the Ngāroto lakes and Lake Kawaupaku. Further, Lake Kawaupaku was not sampled in the spring due to extensive beds of *E. densa* in the littoral zone.

Custom moulded (Cambrian Plastics Ltd, Auckland) clear acrylic domes (400 mm diameter) with an extended bottom flange (100 mm) and a horizontal encircling flange (50 mm) were used to measure groundwater infiltration rates (Figure 9). Two ducts ($\text{Ø} = 6 \text{ mm}$) fitted with valves allowed water passage into and out of the dome to be regulated, and any air bubbles to be vented. Fifty millilitres of ultrapure water was added to a modified empty 1 L saline intravenous bag (Capes Medical, Tauranga) which was then attached to one of the chamber duct valves. The addition of water to the bag reduced the adhesion between the sides of the PVC bag and provided a reservoir to indicate loss of water from the chamber to the lake bottom. The chambers were left overnight and retrieved approximately 24 hours after deployment. Groundwater infiltration rates were determined from the net change in water volume within the bag in relation to chamber area (0.126 m^2) and time (day). It should be

noted that the infiltration volume was too small to determine groundwater nutrient concentrations due to dilution within the infiltration chamber.



Figure 9. Infiltration chamber used to measure littoral groundwater flux.

Lake Profiles and Characteristics

Vertical profiles of lake temperature ($^{\circ}\text{C}$), dissolved oxygen (mg L^{-1}), specific conductivity ($\mu\text{S cm}^{-1}$), chlorophyll fluorescence (Relative fluorescence units) and photosynthetically active radiation (PAR; $\mu\text{mol s}^{-1} \text{m}^{-2}$) were measured using a Seabird electronics 19plus V2 SeaCAT Profiler CTD with auxiliary fluorescence and PAR sensors at each lake during benthic incubation chamber deployment. Thermocline depth, metalimnion extent, euphotic zone depth (Z_{eu}) and light attenuation coefficient (K_d) were calculated using rLakeAnalyzer package (v. 1.11.4.1) in R (v. 4.4.2) (Winslow et al. 2019).

Lake Sediment Nutrient Fluxes

Benthic chamber incubations were conducted between 30 October to 22 November 2023. Nutrient release rates were determined using benthic incubation chambers deployed to the lakebed. Four acrylic chambers (400 mm diameter, area 0.126 m^2 and volume 16.5 L), were deployed approximate to the deepest point of each lake. Dark chambers were exclusively used as all deployment depths were below the lake's euphotic zones, and light chambers were not required to determinate the effect of vegetative uptake of released nutrients. Chambers were deployed by SCUBA divers to minimise sediment disturbance during insertion of the chambers into the sediments. Each chamber was pushed into the sediment to a depth of 100 mm, corresponding to the position of a flange on the outside of each chamber. A duct ($\varnothing = 6 \text{ mm}$) fitted to the crest of the chamber's dome was connected by silicon tubing ($\varnothing = 6 \text{ mm}$) via a one-way check-valve to a surface float allowing water to be pumped from the chamber

to the surface. A second duct and check-valve allowed inflow of ambient lake water when the chamber came under vacuum from the pump. After insertion, the chambers were allowed to settle for 30 minutes before sampling to allow disturbed material to settle. Water in the chambers was mixed throughout the experiment with a submersible 5 V DC pump (Esooho Gikfun, USA; flow rate 1 L minute⁻¹) which circulated water for 5 minutes each hour. For laboratory trials, this mixing regime sufficiently mixed the water within the chamber without resuspending the sediment. Lake bottom water samples were also collected and incubated for the length the chamber deployment in triplicate dark 1 L Nalgene bottles suspended 1 m above the bottom to measure water column nutrient regeneration rates in the absence of bottom sediments.

Each benthic chamber was sampled six times over two days (approximately 0.5, 4, 8, 24, 28 and 32 hours after deployment) by pumping water to the surface via silicon tubing attached to the chamber. Ideally, this should allow sufficient time for the chambers to go anoxic and reach a point where the dissolved nutrient concentrations in the overlying water are in balance with the binding/release capacity of the sediment. Between 100–250 mL of water was pumped from each chamber to flush the tubing, with the volume depending on the depth of chamber deployment. Bottom water was also sampled on each occasion via a Schindler trap taken approximately 1 m from the lakebed. For each water sample, 50 mL was syringe filtered through a 0.45 µm cellulose acetate membrane filter (Minisart, Sartorius) before being placed on ice and returned to the laboratory where the filtrate was frozen before analysis for ammonium (NH₄), nitrate (NO₃) and DRP (Hill Labs, Hamilton). The benthic nutrient flux was calculated by the following (Eq. 1):

$$\text{Flux mg m}^{-2} \text{ day}^{-1} = \frac{(C_{t_{n+1}} \cdot V_1) - (C_{t_n} \cdot (V_1 - V_2) + C_0 \cdot V_2)}{(t_{n+1} - t_n) \times A} \quad (\text{Eq.1})$$

where A is the surface area of the benthic chamber (m²), n is the number of samples, and t_n is the time interval (d). C_0 is the initial concentration (mg L⁻¹), C_t is the concentration (mg L⁻¹) measured in the overlying water at time t (d), and V_1 and V_2 are the volumes before and after sampling of the benthic chamber (L), respectively (Özkundakci et al. 2012).

To provide further application to ecological lake models such as DYRESM-CAEDYM (Hamilton et al. 2018) lake-specific maximum nutrient flux rate at 20°C (S_g) and the oxygen half saturation constant (K_{sOD}) were determined by solving for dissolved nutrient flux (DNF) using the GRG nonlinear solver in Microsoft Excel. The results were then integrated into the following model for DNF from Özkundakci et al. (2012) (Eq. 2) and are plotted with ammonium and DRP sediment release rates.

$$f_g^{DSF} = \vartheta_g^{T-20} S_g \left(\frac{K_{Oxg}}{K_{Oxg} + \Sigma(\text{oxidants})} \right) \quad (\text{Eq.2})$$

where the subscript g used here is a generic identifier for phosphate or ammonium, θ is a temperature multiplier, S_g is the maximum flux at 20°C, K_{ox} is a half-saturation constant that relates the flux to the overlying concentration of oxidants.

Results

Littoral Groundwater Infiltration

Littoral groundwater influxes were measured in the winter and spring of 2023 with the chambers deployed at the same locations on both sampling occasions (Appendix 1). The number of littoral groundwater chambers deployed was often restricted by the higher-than-normal lake levels and dense emergent macrophytes (i.e., *Typha orientalis*) in the littoral zone. No net efflux was measured by any of the chambers, with net groundwater infiltration rates ranging from 1.0–7.4 L m⁻² day⁻¹. Apart from Spectacle Lake, infiltration rates were generally higher in the spring, with rates being higher in the Ngāroto Lakes (Slipper, Spectacle, Tomarata) on the east coast compared to the west coast lakes (Table 1). Elevated infiltration rates in Slipper Lake on 30 October 2023 were associated with heavy rainfall (>100 mm) in the 36-hour period prior to chamber deployment.

Table 1. Winter and spring littoral groundwater infiltration rates for seven Auckland dune lakes.

	No. of chambers	Lake littoral infiltration rate (L m ⁻² day ⁻¹)				
		Winter		Spring		Annual
		Mean	Range	Mean	Range	Mean
Kawaupaku	1	1.0	1.0	N/D	–	1.0
Ōkaihau	3	N/D*	–	3.2	2.0–4.6	3.2
Te Kanae	3	2.3	1.5–5.5	3.7	3.2–4.2	3.0
Whatihua	3	3.3	2.2–4.1	5.3	4.2–7.2	4.3
Slipper	1	1.0	1.0	7.8	7.8	4.4
Spectacle	2	4.0	3.7–4.2	3.3	2.2–4.3	3.6
Tomarata	4	3.8	1.7–5.4	5.3	3.7–4.6	4.6

*Site was not accessible.

It was assumed that the lake littoral zone extended from zero to one meter depth. Estimates of daily and annual groundwater infiltration volumes were calculated for each lake by multiplication of the littoral zone area by the annual mean infiltration rate (Table 2). It should be noted that the area of the littoral zones was determined from hypsographic data based on mean lake elevation, however, lake levels were substantially elevated (by approximately 1–

1.5 m) when sampling was conducted in 2023. Further, infiltration rates were likely higher than normal due to exceptionally high rainfall during the first half of 2023.

Table 2. Estimated daily and annual groundwater infiltration volume from the littoral zone (0–1 m depth).

Lake	Littoral zone area at 0-1 m depth (m ²)	Mean daily infiltration (L m ⁻² day ⁻¹)	Daily lake littoral zone infiltration (m ³ day ⁻¹)	Lake littoral zone annual infiltration volume (m ³ y ⁻¹)	Lake volume (m ³)	Proportion of lake volume
Kawaupaku	3,286	1.0	3.3	1,200	830,350	<0.01
Okaihau	19,439	3.2	62.2	22,720	214,228	0.11
Te Kanae	1,479	3.0	4.4	1,621	429,679	<0.01
Whatihua	19,310	4.3	83.0	30,328	92,672	0.33
Slipper	4,481	4.4	19.7	7,201	193,220	0.04
Spectacle	14,912	3.6	53.7	19,608	1,023,020	0.02
Tomarata	7,731	4.6	35.6	12,989	239,265	0.05

Individual chamber groundwater infiltration rates were weakly positively related to the linear distance between the chamber location and the approximate surface catchment boundary for both the winter and spring sampling (Figure 10).

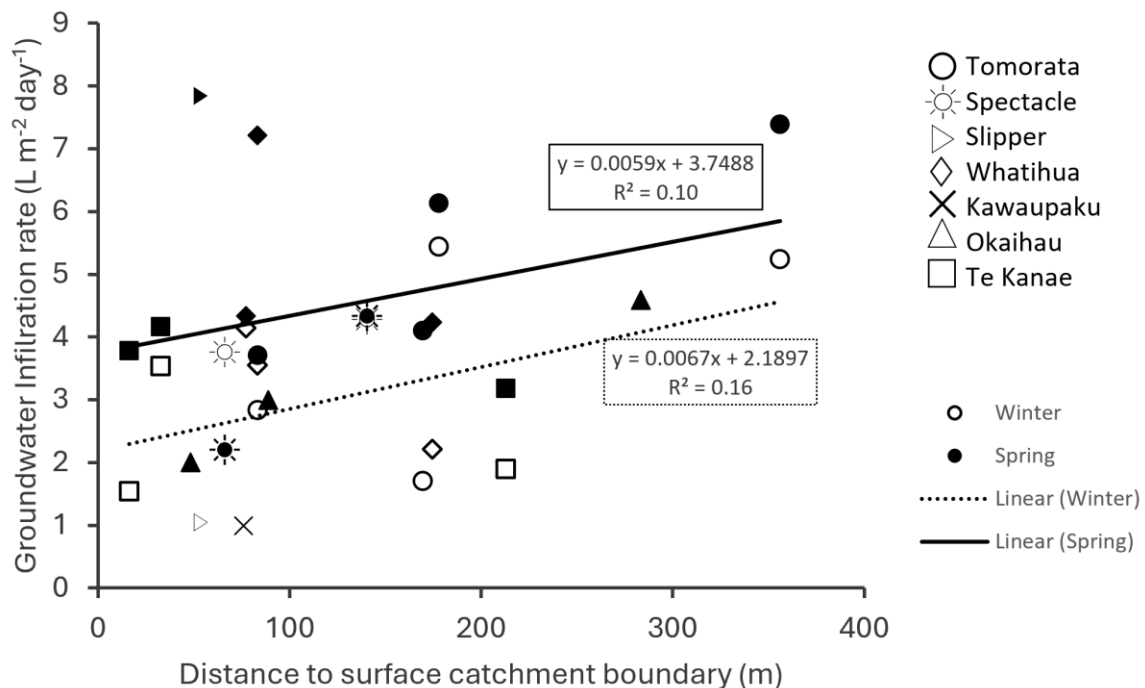


Figure 10. Winter and spring littoral groundwater infiltration rates for individual chambers in relation to chamber distance to surface catchment boundaries.

Lake Profiles and Characteristics

Vertical lake profiles of temperature ($^{\circ}\text{C}$), dissolved oxygen (% sat.), fluorescence (RFU), photosynthetically active radiation (PAR; $\mu\text{mol s}^{-1} \text{m}^{-2}$) and specific conductivity ($\mu\text{S cm}^{-1}$) were measured for each lake during benthic chamber deployment. Temperature and dissolved oxygen profiles indicate that lakes Whatihua (Figure 11), Ōkaihau (Figure 12) and Te Kanae (Figure 13) were strongly stratified by November 2023, with the hypolimnion completely anoxic. Notably, Lake Kawaupaku (Figure 14) appeared to have recently mixed with the thermocline reforming and the hypolimnion becoming anoxic during the deployment. Spectacle (Figure 15) and Slipper (Figure 16) Lakes were mixed, although there was evidence of hypoxia near the bottom of Spectacle Lake. Lake Tomarata (Figure 17) was weakly thermally stratified, but dissolved oxygen levels were above 70% saturation near the lakebed. Thermocline depth and extent of metalimnion, where present, were calculated for each lake along with euphotic zone depth (Z_{eu}) and light attenuation coefficient (K_{d}) (Table 3). Photosynthetically active radiation was highly attenuated in Lake Kawaupaku which was supported by the observation that the water was highly turbid due to suspended sediment at the time of sampling and the fluorescence profile indicated that phytoplankton were restricted to a maximum depth of approximately 1.5 m. Light attenuation was also notably higher in Lake Tomarata compared to the other lakes, although this could be attributed to the dystrophic conditions. Chlorophyll a fluorescence profiles of lakes Whatihua and Ōkaihau evidenced distinct deep chlorophyll maxima, with fluorescence exceeding the maximum scale of the instrument in Lake Whatihua (Figure 11).

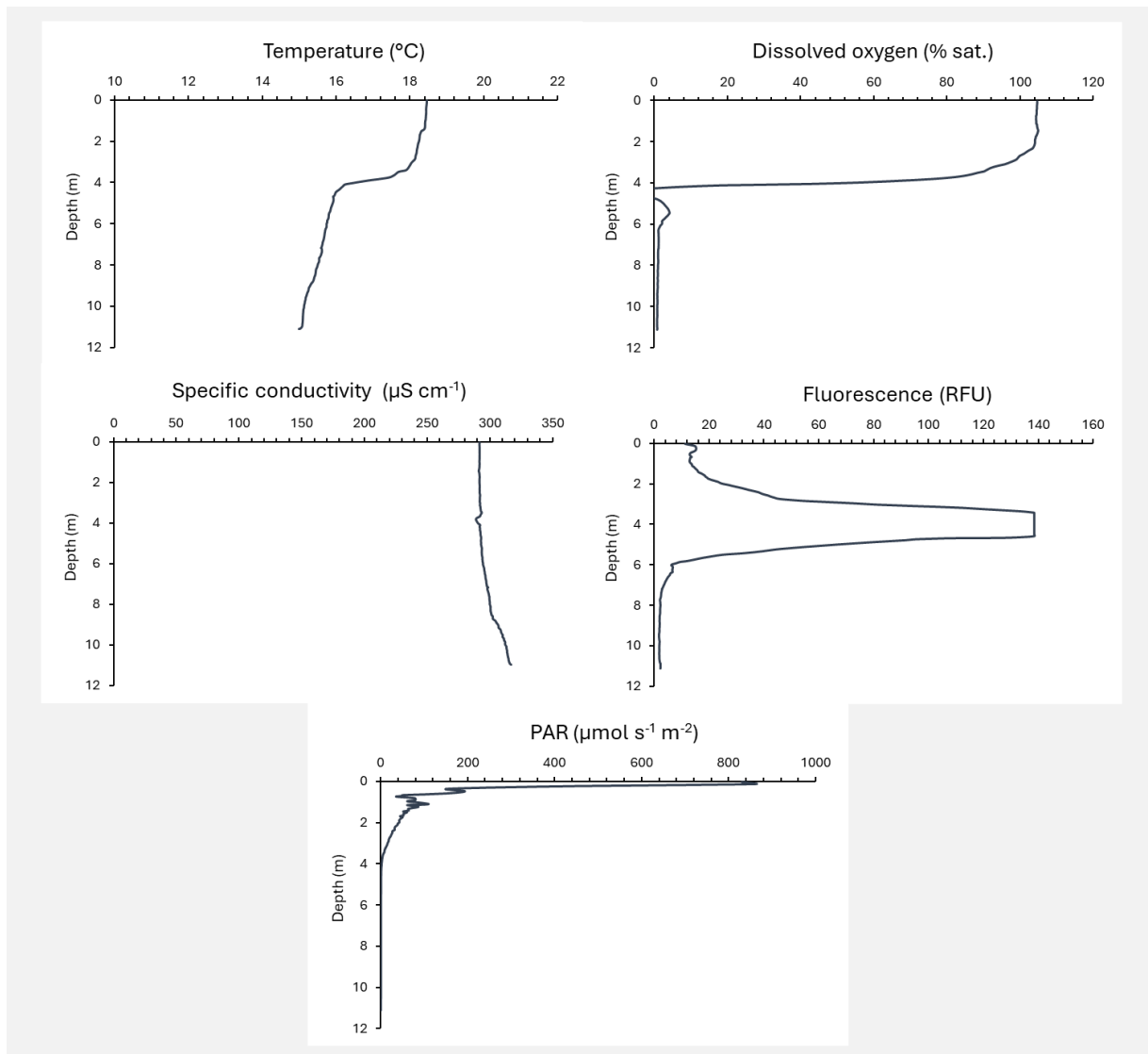


Figure 11. Vertical lake profiles of temperature (°C), dissolved oxygen (% sat.), fluorescence (RFU), photosynthetically active radiation (PAR; $\mu\text{mol s}^{-1} \text{m}^{-2}$) and specific conductivity ($\mu\text{S cm}^{-1}$) in Lake Whatihua, 9 November 2023. Note: Instrument fluorescence maximum was reached at 140 RFU.

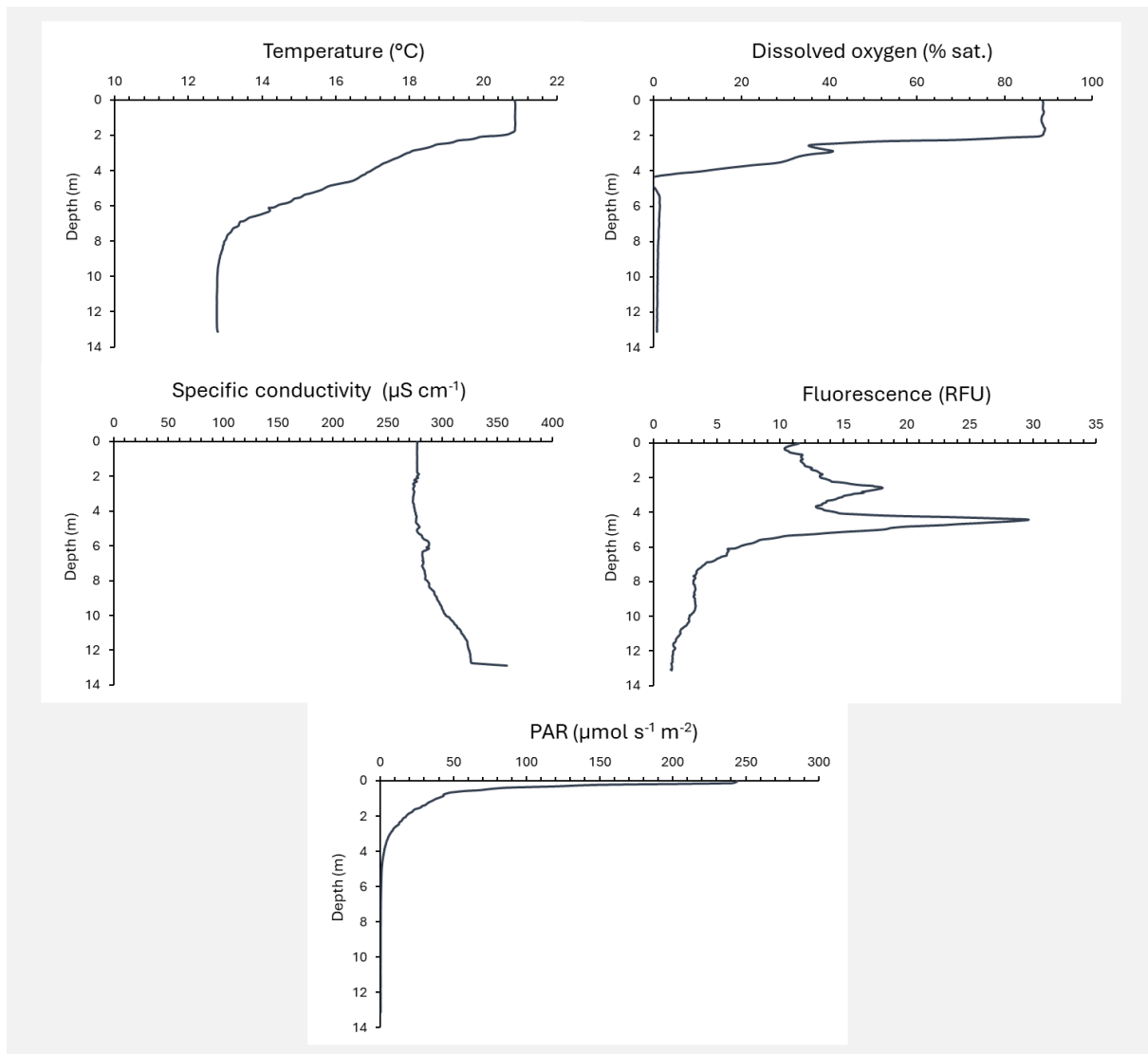


Figure 12. Vertical lake profiles of temperature (°C), dissolved oxygen (% sat.), fluorescence (RFU), photosynthetically active radiation (PAR; $\mu\text{mol s}^{-1} \text{m}^{-2}$) and specific conductivity ($\mu\text{S cm}^{-1}$) in Lake Ōkaihou, 14 November 2023.

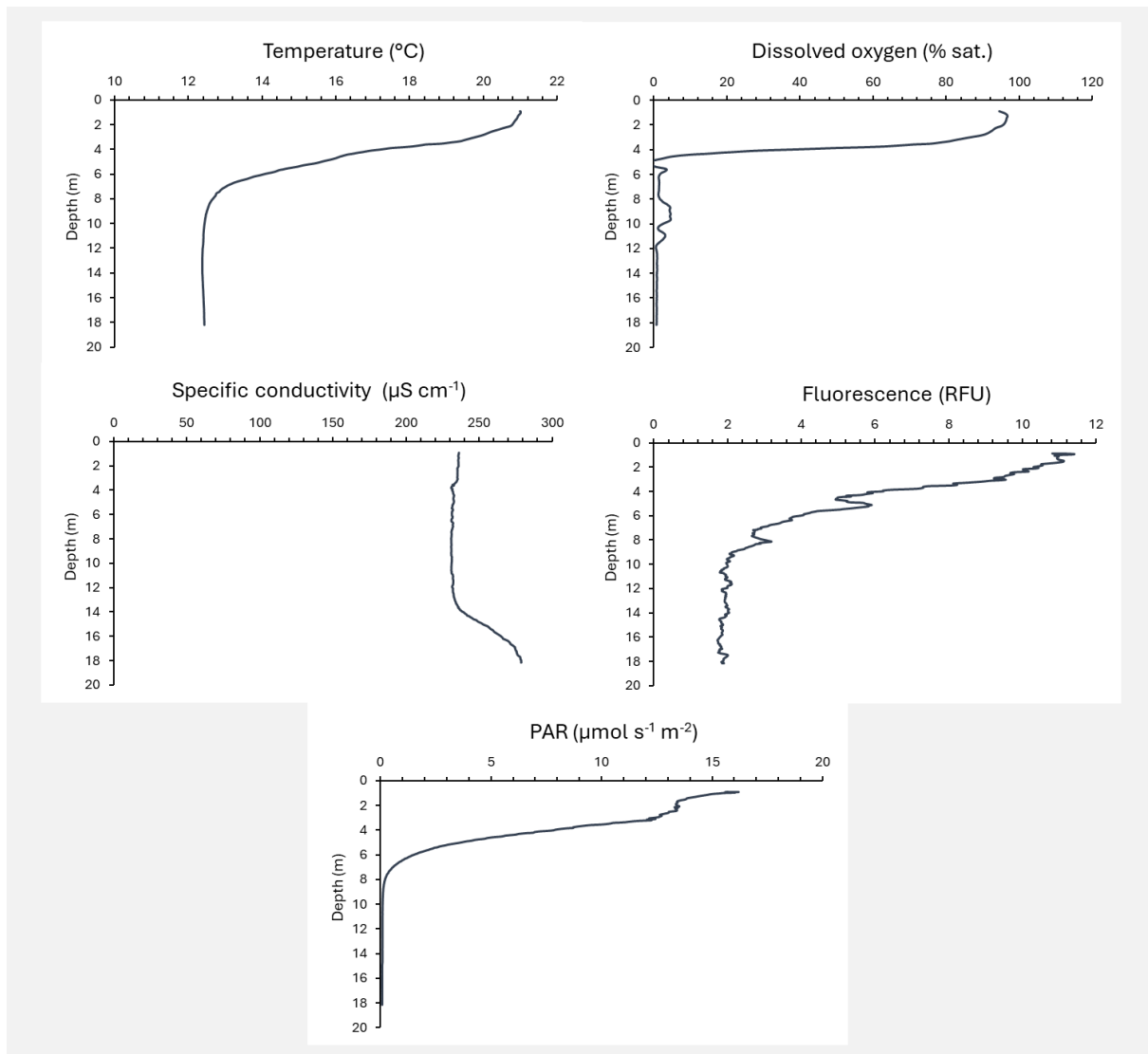


Figure 13. Vertical lake profiles of temperature (°C), dissolved oxygen (% sat.), fluorescence (RFU), photosynthetically active radiation (PAR; $\mu\text{mol s}^{-1} \text{m}^{-2}$) and specific conductivity ($\mu\text{S cm}^{-1}$) in Lake Te Kanae, 22 November 2023.

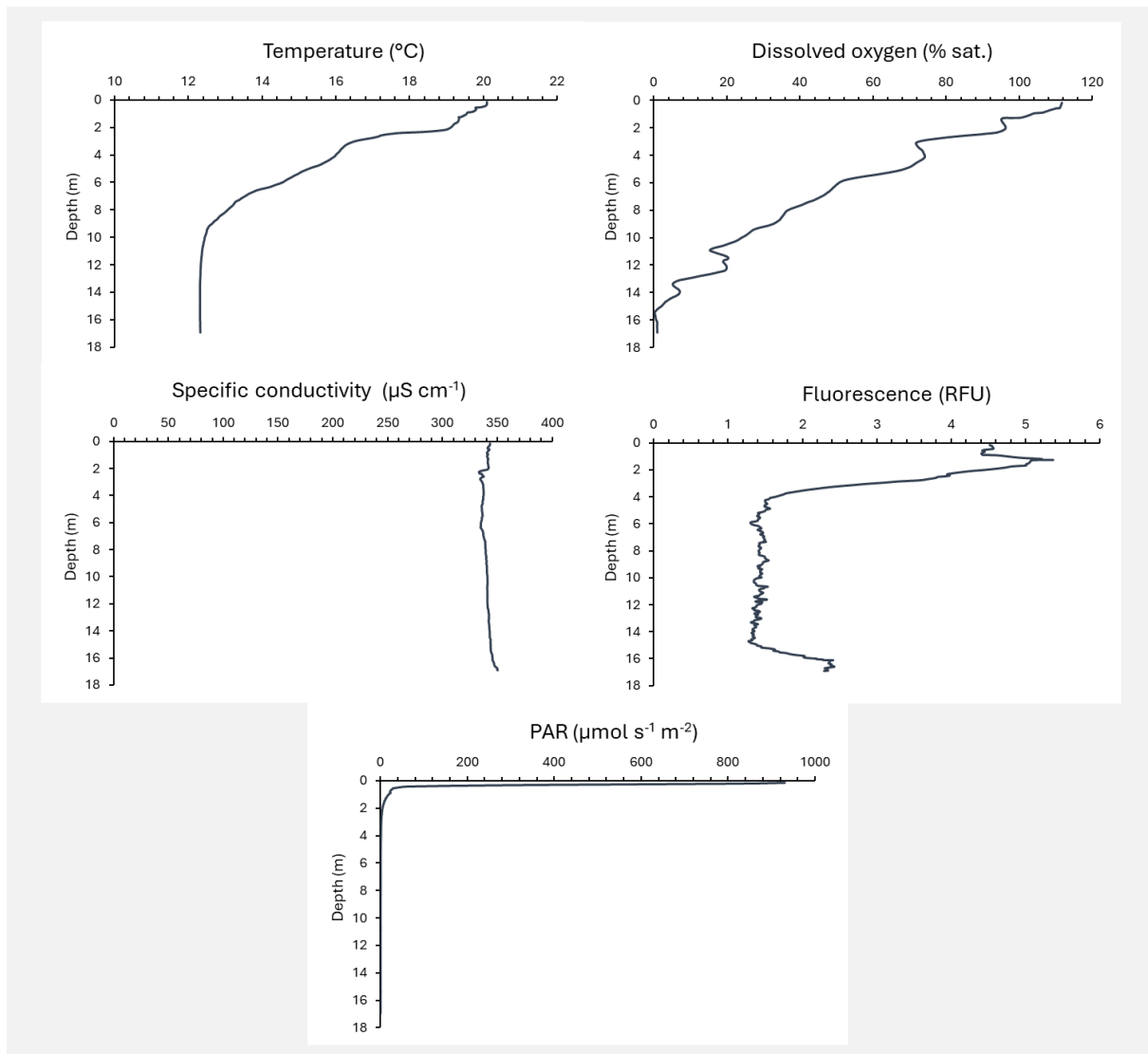


Figure 14. Vertical lake profiles of temperature ($^{\circ}\text{C}$), dissolved oxygen (% sat.), fluorescence (RFU), photosynthetically active radiation (PAR; $\mu\text{mol s}^{-1} \text{m}^{-2}$) and specific conductivity ($\mu\text{S cm}^{-1}$) in Lake Kawaupaku, 15 November 2023.

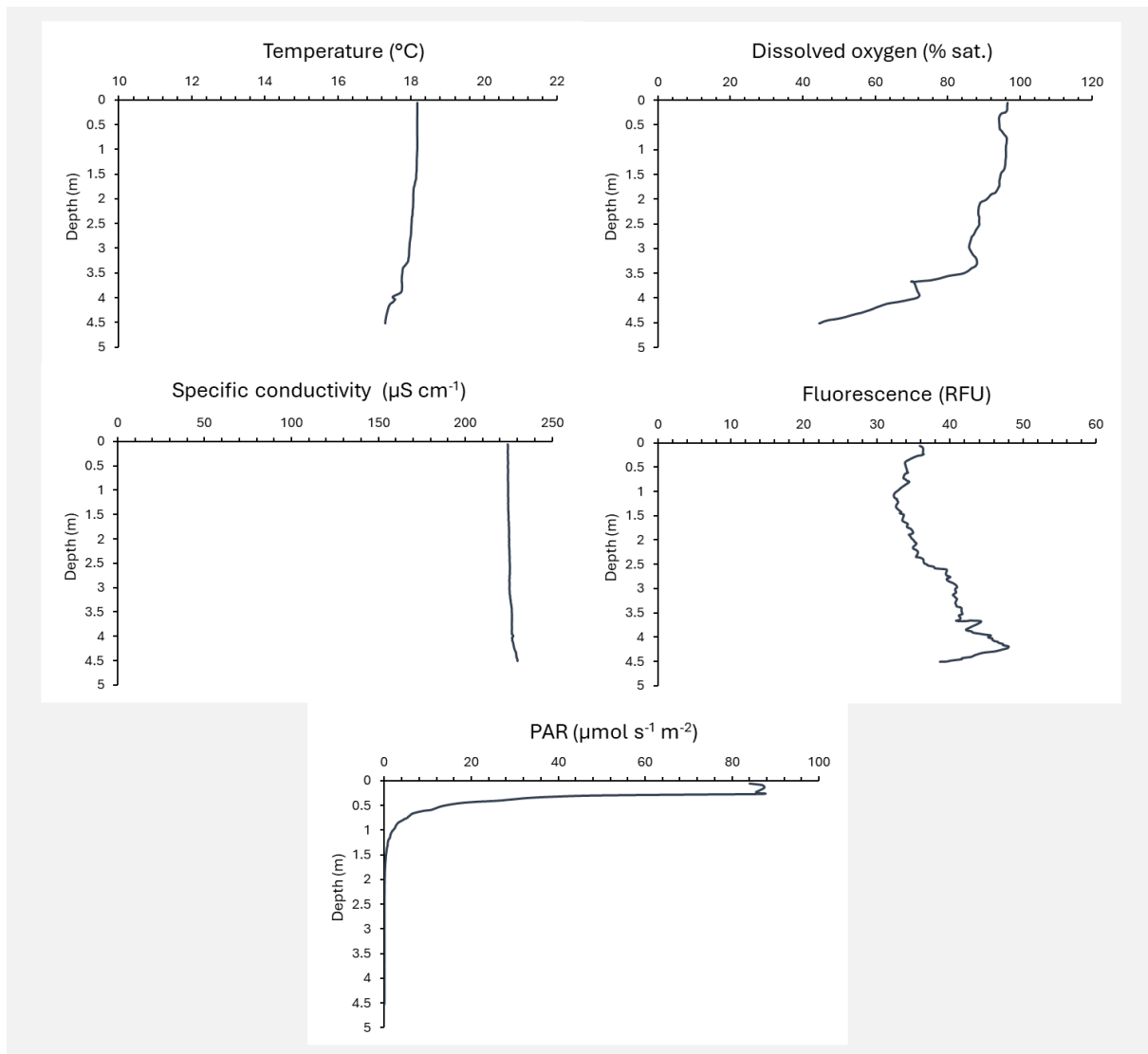


Figure 15. Vertical lake profiles of temperature (°C), dissolved oxygen (% sat.), fluorescence (RFU), photosynthetically active radiation (PAR; $\mu\text{mol s}^{-1} \text{m}^{-2}$) and specific conductivity ($\mu\text{S cm}^{-1}$) in Spectacle Lake, 3 November 2023.

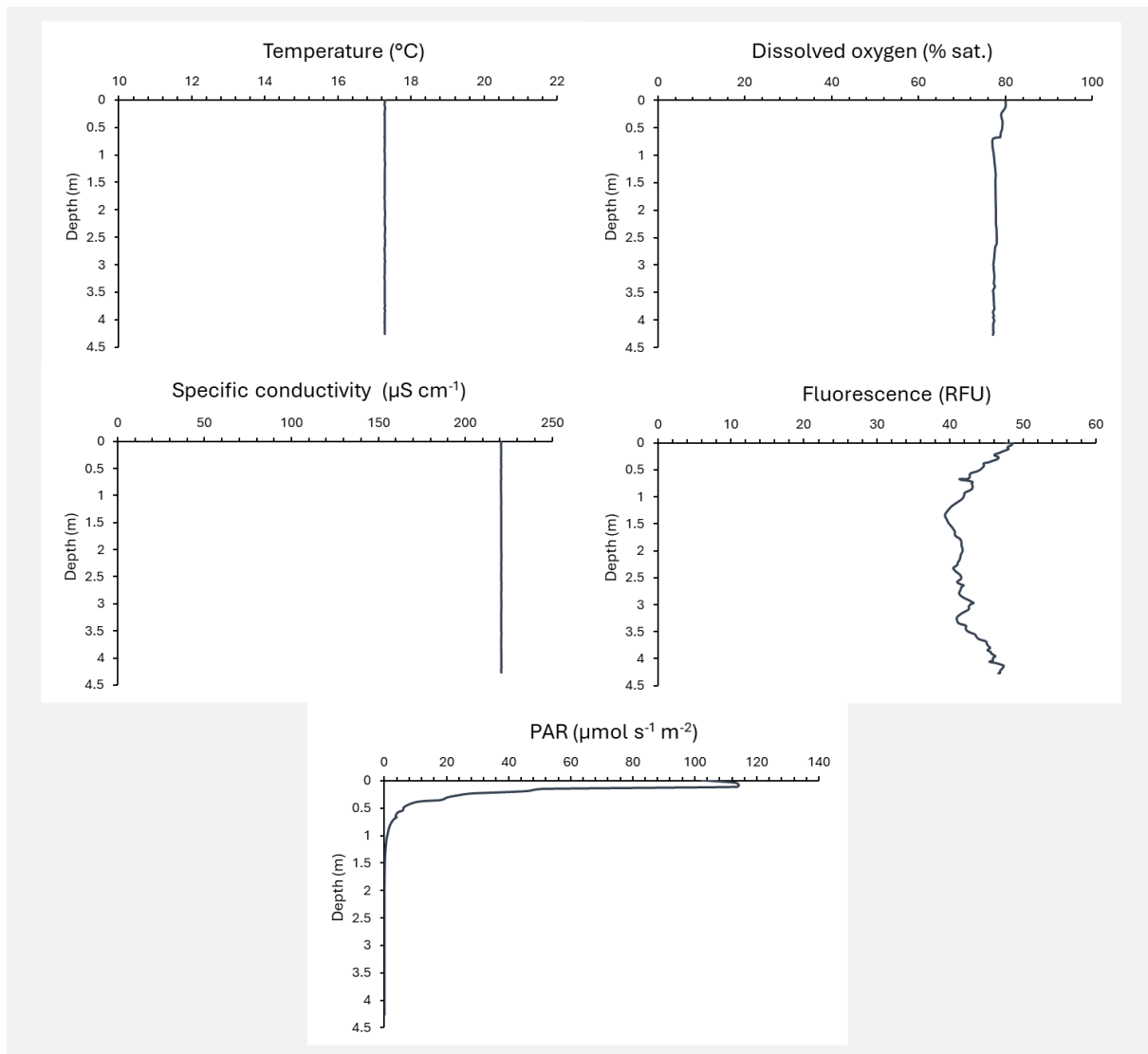


Figure 16. Vertical lake profiles of temperature (°C), dissolved oxygen (% sat.), fluorescence (RFU), photosynthetically active radiation (PAR; $\mu\text{mol s}^{-1} \text{m}^{-2}$) and specific conductivity ($\mu\text{S cm}^{-1}$) in Slipper Lake, 30 October 2023.

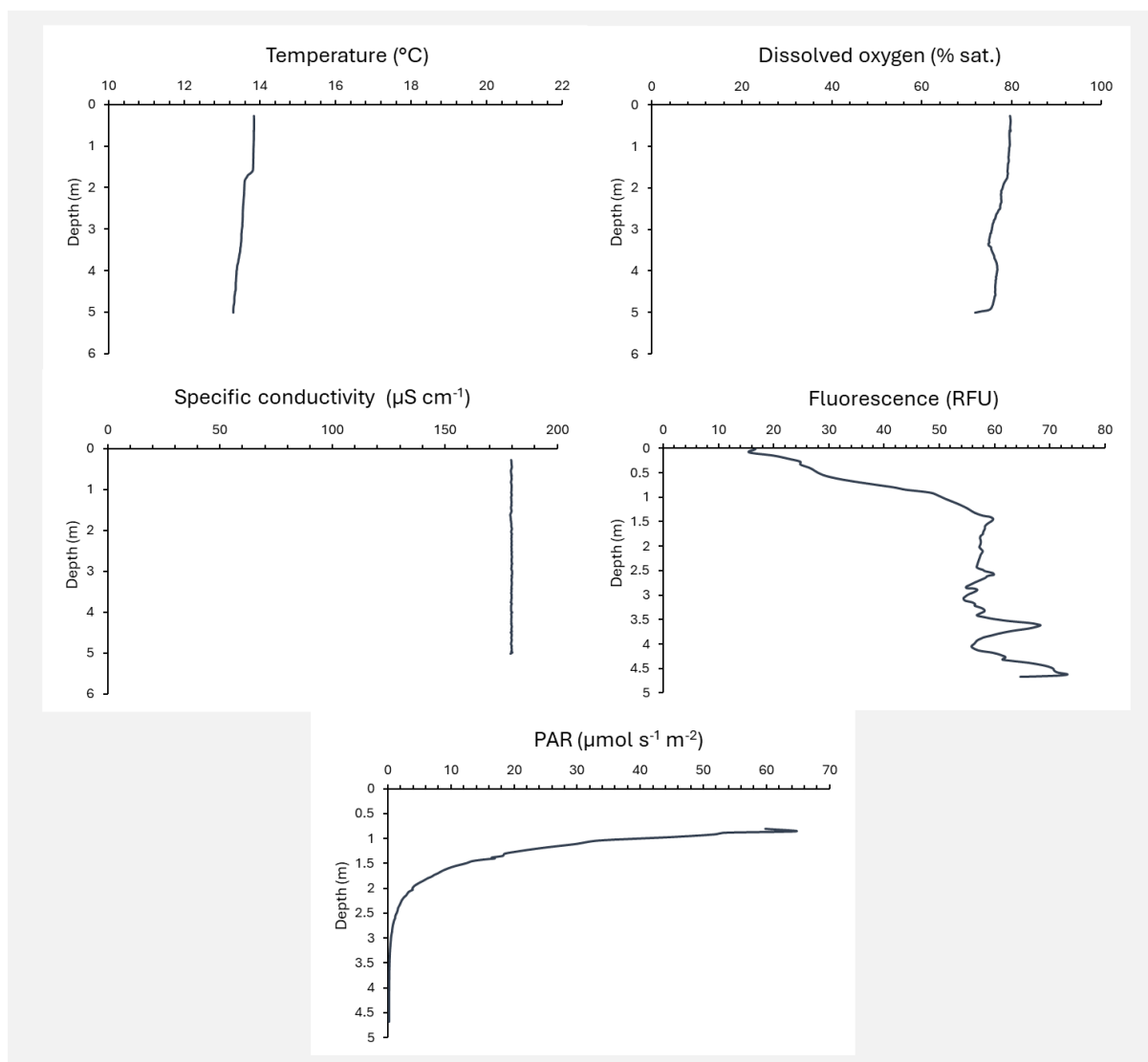


Figure 17. Vertical lake profiles of temperature (°C), dissolved oxygen (% sat.), fluorescence (RFU), photosynthetically active radiation (PAR; $\mu\text{mol s}^{-1} \text{m}^{-2}$) and specific conductivity ($\mu\text{S cm}^{-1}$) in Lake Tomarata, 23 August 2024.

Table 3. Thermocline depth, metalimnion extent, euphotic zone depth (Z_{eu}) and light attenuation coefficient (K_d) for seven Auckland dune lakes. NA indicates the parameter is not applicable due to the lake being fully mixed

Lake	Sampling date	Thermocline depth (m)	Metalimnion top (m)	Metalimnion bottom (m)	Z_{eu} (m)	K_d (m^{-1})
Kawaupaku	15/11/23	4.51	2.09	9.60	1.5	10.5
Ōkaihau	14/11/23	2.37	2.05	3.28	4.0	0.99
Te Kanae	22/11/23	6.10	3.06	6.72	4.1	0.81
Whatihua	9/11/23	3.80	3.43	4.87	3.4	0.94
Slipper	30/10/23	NA	NA	NA	1.0	0.99
Spectacle	3/11/23	NA	NA	NA	1.2	0.82
Tomarata	23/08/24	1.72	1.61	1.90	1.6	2.37

Dissolved nutrient concentrations (ammonium, nitrate, nitrite and DRP) were measured from water sampled approximately 1 m from the lakebed at the start of chamber deployment. Ammonium concentrations ranged from 0.01–0.56 mg N L⁻¹ with a mean of 0.14 mg N L⁻¹. Apart from Kawaupaku (0.54 mg N L⁻¹) nitrate and nitrite concentrations were near or below detection limits (<0.002 mg N L⁻¹), and DRP concentrations were close to the analytical detection limits (<0.004 mg P L⁻¹) with Spectacle Lake having the highest bottom water DRP concentration of 0.017 mg P L⁻¹ (Table 4).

Table 4. Dissolved nutrient concentrations (ammonium, nitrate, nitrite and dissolved reactive phosphorus (DRP)) sampled from bottom waters of seven Auckland dune lakes.

Lake	Sample date	Ammonium (mg N L ⁻¹)	Nitrate (mg N L ⁻¹)	Nitrite (mg N L ⁻¹)	DRP (mg P L ⁻¹)
Kawaupaku	15/11/2023	0.024	0.540	<0.002	0.005
Ōkaihau	8/11/2023	0.560	<0.002	<0.002	0.004
Te Kanae	21/11/2023	0.220	0.005	0.004	<0.004
Whatihua	8/11/2023	0.020	<0.002	<0.002	0.007
Slipper	30/10/2023	0.024	0.002	0.003	0.012
Spectacle	3/11/2023	0.011	<0.002	<0.002	0.017
Tomarata	19/08/2024	0.148	0.068	0.007	<0.004

Lake Sediment Nutrient Fluxes

Due to the anoxic hypolimnetic conditions in lakes Kawaupaku, Ōkaihau, Te Kanae and Whatihua, sediment nutrient release rates could not be determined as the lakes were already anoxic. Benthic chambers were deployed to Lake Tomarata in early November 2023, but dissolved oxygen declined to ~40% saturation after 38 hours, and a second deployment was conducted in August 2024. Consequently, sediment nutrient fluxes were only quantified for Tomarata, Slipper, and Spectacle lakes.

There was no detectable DRP release from the sediment after 68 hours in Lake Tomarata. However, the ammonium release rate was 1.26 mg m⁻² day⁻¹ with the greatest flux occurring when dissolved oxygen declined to <4 mg L⁻¹ (Table 5; Figure 18). Ammonium release started to decline approximately 30 hours after deployment ($f(\text{NH}_4)$; Figure 18), with the calculated maximum flux at 20°C of 1.97 mg m⁻² day⁻¹ similar to the measured ammonium flux rate.

Table 5. Sediment dissolved reactive phosphorus (DRP) and ammonium flux rates, maximum nutrient flux rate at 20°C ($S_{(g)}$) and half saturation constant for oxygen (K_{ox}) for lakes Tomarata, Spectacle and Slipper.

Lake	Nutrient	Measured flux rate ($\text{mg m}^{-2} \text{ day}^{-1}$)	$S_{(g)}$ ($\text{mg m}^{-2} \text{ day}^{-1}$)	K_{ox}
Lake Tomarata	DRP	-	-	-
	Ammonium	1.26	1.97	5.5
Slipper Lake	DRP	1.10	1.41	7.0
	Ammonium	4.84	6.47	4.4
Spectacle Lake	DRP	1.16	1.59	7.1
	Ammonium	2.73	3.64	8.5

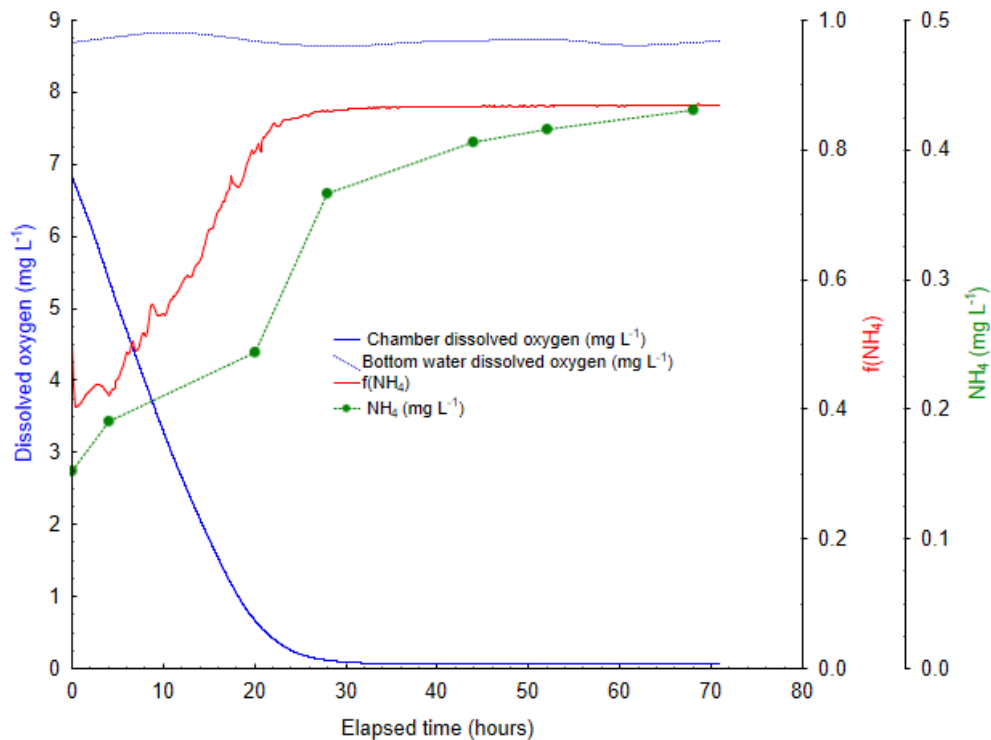


Figure 18. Changes in ammonium (NH_4) and dissolved oxygen in benthic incubation chambers and bottom waters of Lake Tomarata. Also presented is the plotted function of the calculated ammonium flux at 20°C ($f(\text{NH}_4)$).

Benthic chamber dissolved oxygen rapidly declined in Slipper Lake reaching $<2 \text{ mg L}^{-1}$ 7 hours after deployment (Figure 19). However, after initially increasing over the first 4 hours of deployment, DRP concentrations remained relatively consistent over the remaining incubation period despite anoxia occurring 20 hours following deployment. In contrast, ammonium concentrations increased throughout the deployment period but did not plateau,

indicating the concentration was unlikely to have reached saturation by the end of the deployment period (Figure 19).

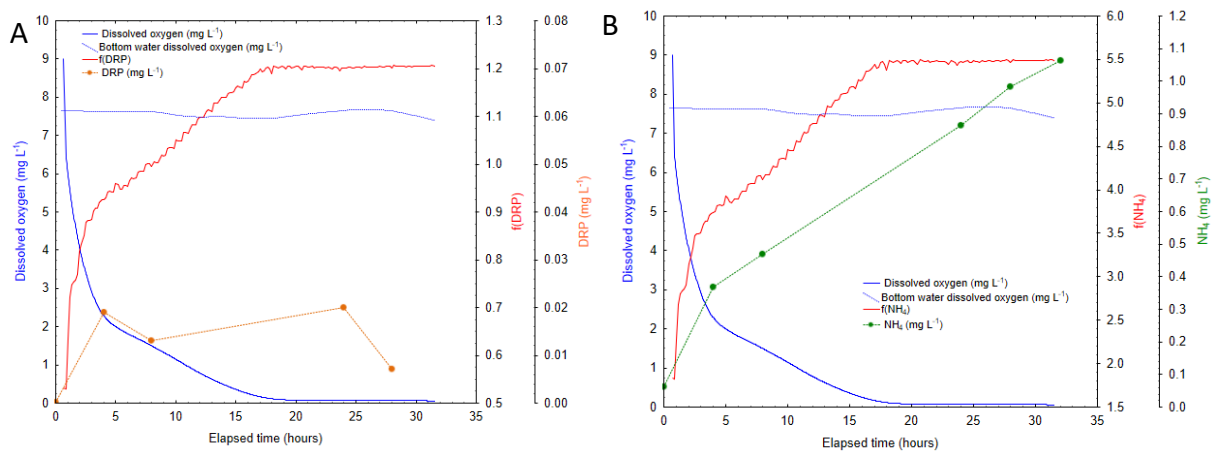


Figure 19. Changes in (A) dissolved reactive phosphorus (DRP) and, (B) ammonium (NH₄) in relation to dissolved oxygen concentrations in benthic incubation chambers and bottom waters of Slipper Lake. Also presented are the plotted function of the calculated DRP and ammonium fluxes at 20°C (f (DRP) and f(NH₄)).

Dissolved oxygen initially declined rapidly in Spectacle Lake, but the chambers only became anoxic after 30 hours (Figure 20). Of note, hypolimnetic oxygen concentrations varied from <5 mg L⁻¹ to >8 mg L⁻¹ within a 24-hour period the chamber deployment. As with Slipper Lake, sediment DRP concentrations did not show a marked response until dissolved oxygen declined below 2 mg L⁻¹, while ammonium concentrations increased following dissolved oxygen declining below 4 mg L⁻¹. The slower than anticipated decline in chamber dissolved oxygen concentrations meant that both ammonium and DRP concentrations likely did not reach their saturation points.

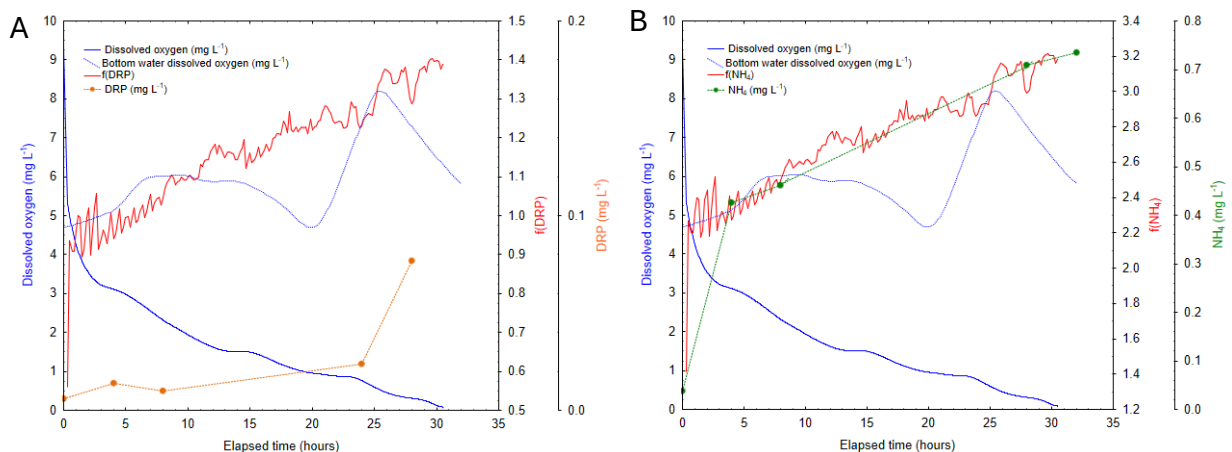


Figure 20. Changes in (A) dissolved reactive phosphorus (DRP) and, (B) ammonium (NH₄) in relation to dissolved oxygen concentrations in benthic incubation chambers and bottom waters of Spectacle Lake. Also presented are the plotted function of the calculated DRP and ammonium fluxes at 20°C (f (DRP) and f(NH₄)).

Discussion

Lake littoral groundwater infiltration rates were determined for seven dune lakes in the Auckland Region. Sediment nutrient fluxes were determined for the three east coast lakes (Tomarata, Spectacle and Slipper lakes), but the four west coast lakes experience prolonged periods of stratification and with anoxic hypolimnia, preventing evaluation of nutrient flux rates. Where possible, lake sediment nutrient fluxes were calculated to produce areal sediment release rates for DRP and ammonium. This information was then used to calculate maximum nutrient flux rate at 20°C (S_g) and the half saturation constant for oxygen (K_{ox}) which could then be integrated into ecological models such as DYRESM-CAEDYM. Incorporating site-specific parameter values should improve accuracy of model simulations.

Littoral Groundwater Infiltration

High lake levels and extensive riparian vegetation restricted the number of infiltration chambers that were deployed. However, the sandy composition of the littoral sediment and the surrounding soils was well-suited for measuring groundwater infiltration rates, allowing a good seal between the chamber and the sediment with no gas ebullition following deployment. The comparatively small, steep sided and free draining catchments resulted in restricted or no surface inflows indicating that the lakes were primarily groundwater fed. In addition, surface outflows were not substantial, with lakes Whatihua, Te Kanae and Ōkaihau having no surface outflows.

Littoral groundwater infiltration rates were roughly proportional to the estimated linear distance to the catchment boundary, and likely heavily influenced by rainfall in the 24–48-hour period prior to measurement. Similar infiltration rates and relationships to the catchment have been observed at free draining areas of Lake Tarawera using the same methodology (S. Tetzlaff and G. Tempero, unpublished data), Lake Tegal in Germany (Hoffmann and Gunkel 2011) and Oneida Lake in the United States (Schneider et al. 2005). Estimates of daily and annual littoral groundwater infiltration rates for the Auckland dune lakes were calculated, with the proportion of annual littoral infiltration volume to lake volume ranging from <0.005 to 0.33. However, it should be noted that at the time of sampling lake levels were well about normal (by approximately 1–1.5 m) and the restricted number of seepage chambers deployed means these estimates should be treated with caution. However, the littoral seepage chambers were relatively simple and cost effective to deploy, and further studies coupling them with piezometers, analysis of groundwater isotopic composition to determine groundwater age and source, and hydrologic modelling would aid in providing improved quantification of the hydrodynamics and external nutrient loading in these dune lakes. The determination of groundwater contribution to lake nutrient loading is of particular importance given inputs from surface flows appear to be only a small component of the overall nutrient loading to these lakes.

Lake Profiles and Characteristics

Located on the west coast of the Auckland region lakes Kawaupaku, Ōkaihau and Te Kanae were characterised by small, steep sided catchments and low lake surface area to volume ratios (Appendix 2). These characteristics support prolonged lake stratification as wind fetch is insufficient to induce mixing, and the lake only overturns when epilimnetic temperature reaches equilibrium with the lake's hypolimnetic water temperature (Boehrer and Schultze 2008). This results in extended periods of dissolved oxygen depletion to the point of anoxia in the hypolimnion, which may persist near the bottom sediments over the winter (Boehrer and Schultze 2008). This occurs in subtropical climates such as the Auckland region, where shorter periods of low air temperatures coupled with low wind fetch results in only partial mixing of the water column before stratification re-forms (MacIntyre and Melack 2010). Auckland Council environmental monitoring data for lakes Ōkaihau and Kawaupaku for the years 2022–2023 period indicates that the bottom sediments were likely anoxic ($<1 \text{ mg L}^{-1}$) or at least hypoxic ($1\text{--}3 \text{ mg L}^{-1}$) during the winter of these years (Appendix 3).

Persistent anoxia or hypoxia of bottom sediments is also supported by the low DRP concentrations observed in the hypolimnion of lakes Kawaupaku, Ōkaihau and Te Kanae (Table 4). Dissolved reactive phosphorus concentrations in the lake hypolimnia generally increase under reducing conditions, as labile phosphorus is released from iron oxides such as Fe(III) oxyhydroxides as they are reduced to Fe(II) forms (Søndergaard et al. 2003; Anderson et al. 2021). When lakes mix and oxic conditions are restored this process reverses as DRP sequestered by the precipitating Fe(III) hydroxide floc (Amirbahman et al. 2003). While factors such as microbial decomposition, pH, humic content and water hardness are known to regulate DRP availability (Hupfer and Lewandowski 2008), the low DRP concentrations in relation to abundant ammonia (or nitrate in the more oxic Kawaupaku; Table 4) suggest that phosphorus is naturally limited in these lakes. Phosphorus limitation is also indicated by the TN:TP mass ratios derived from Auckland Council monitoring data for the years 2022–2023, with ratios of 22:1 for Te Kanae, 20:1 for Kawaupaku and 18:1 for Ōkaihau all exceeding the 15:1 mass ratio indicative of phosphorus limitation in New Zealand lakes (Abell et al. 2010).

Lake Sediment Nutrient Fluxes

Sediment nutrient release rates could not be determined for lakes Kawaupaku, Ōkaihau, Te Kanae and Whatihua due to anoxia in the hypolimnion at the time of the chamber deployment. The small catchments of these lakes limit the volume of surface inflows; this restricts external phosphorus loading, as surface flow is the primary vector for external phosphorus loading (Hamilton et al. 2018). When taken in conjunction with the high TN:TP ratios of these lakes, it is likely that sediment phosphorus cycling is restricted compared to eutrophic polymictic lakes such as Lake Rotorua (Burger et al. 2007). In contrast to phosphorus, nitrogen moves more readily through the root zone and into groundwater (Hamilton et al. 2018). As the dune lakes in this study are primarily groundwater fed it is not unexpected that bottom water ammonium concentrations in lakes Te Kanae and Okaihu, and

nitrate in Lake Kawaupaku were notably elevated in comparison to DRP concentrations (Table 4). Although the geomorphology of Lake Whatihua is somewhat similar to the other west coast dune lakes in this study, dissolved nutrient concentrations were not notably elevated in the bottom waters at the time of sampling in early November. Monitoring data of the bottom water oxygen concentrations indicates that Whatihua may be more polymictic in nature than Te Kanae, Okaihu and Kawaupaku (Appendix 3). Intermittent mixing of the water column disperses nutrients accumulated in the hypolimnion into the photic zone where they drive the formation of algal blooms (Hamilton et al. 2018), as was evidenced by the intensive deep chlorophyll *a* maxima present in Whatihua at the time of sampling.

The shallow, polymictic nature of the Ngāroto lakes provided better conditions for determining in situ sediment nutrient fluxes. Such polymictic lakes stratify for short periods (days–weeks) and the bottom waters quickly deoxygenate resulting in short bursts of nutrient release (Hamilton et al. 2018). Initial deployment of the chambers in Lake Tomarata failed to achieve anoxia after 38 hours in November 2023, and a second attempt was made in August 2024, with the chambers deployed for 68 hours. Sediment ammonium flux increased with decreasing dissolved oxygen, with the maximum release occurring when dissolved oxygen was $<2 \text{ mg L}^{-1}$. Chamber hypoxia was achieved approximately 20 hours after deployment, but sediment ammonia flux did not appear to have reached equilibrium by the end of deployment at 68 hours. The measured ammonium flux rate of $1.26 \text{ mg N m}^{-2} \text{ day}^{-1}$ was nearly two orders of magnitude lower than $43.8\text{--}93.5 \text{ mg N m}^{-2} \text{ day}^{-1}$ reported by Burger et al. (2007) for Lake Rotorua in August 2003. However, Lake Rotorua sediments were composed of fine muds and likely nutrient enriched due to lake eutrophication from treated wastewater disposal, which was halted in 1991 (Burger et al. 2007). Sandy sediments from Saginaw Bay, Lake Huron (Michigan, USA) also had substantial ammonium release rates ranging from $43.8\text{--}93.5 \text{ mg N m}^{-2} \text{ day}^{-1}$, however, these were measured in the summer and in an area considered eutrophic with much of the loading originating from the Saginaw River (Gardner et al. 2001). In more nutrient poor systems, ammonium release rates ranging from $0\text{--}5 \text{ mg N m}^{-2} \text{ day}^{-1}$ have been reported (Seitzinger 1987; Beutel and Horne 2018). Ammonium flux rates for Spectacle ($2.73 \text{ mg N m}^{-2} \text{ day}^{-1}$) and Slipper ($4.84 \text{ mg N m}^{-2} \text{ day}^{-1}$) lakes were higher than Lake Tomarata, but lower than would be expected for eutrophic lakes (Tartari and Biasci 1997). The bottom sediments of Slipper and Spectacle lakes appeared to be composed of more organic muds than Lake Tomarata and had larger proportions of the catchment in pastoral land use which may explain the higher ammonium release rates.

Dissolved reactive phosphorus release rates were low for Slipper and Spectacle lakes, and no detectable change in DRP concentrations could be determined for Lake Tomarata. Phosphorus release rates of between $4\text{--}10 \text{ mg P m}^{-2} \text{ day}^{-1}$ have been reported for seven eutrophic lakes in the United States (Sonzogni et al. 1977) and rates of $2.1\text{--}5.6 \text{ mg P m}^{-2} \text{ day}^{-1}$ were reported for eutrophic Lake Rotorua in August 2003 (Burger et al. 2007) using in situ benthic chambers. The low phosphorus release rates may be due to low external phosphorus

loading associated with reduced sediment loading from ephemeral surface inflows, as was observed for the west coast dune lakes. Additionally, sediment geochemistry analysis conducted by Lakes380 for Lake Tomarata found that, despite sediment iron content being reasonably high, the lake had a low redox sensitive phosphorus fraction (8.04% of TP c.f. 21.0% New Zealand average; range 0.6–73.4%) (Waters 2022). This explains why ammonium release, but not DRP release, was detected in Lake Tomarata.

The Auckland dune lakes in this study generally had low catchment area to lake surface area ratios in addition to low surface area to volume ratios (Appendix 2). Dune lake catchments are relatively free draining, often without permanent surface inflows and outflows. This results in deep lakes which occupy a comparatively small catchment and are primarily fed by groundwater. Littoral groundwater inflows likely constitute a significant proportion of the inflow to these lakes and appears volumetrically proportional to the linear distance to the catchment boundary and to variance in catchment rainfall. The Auckland dune lakes littoral infiltration rates appeared to respond relatively quickly (<24 hours) to preceding precipitation; however, this may be partially due to the higher-than-average rainfall and soil saturation during the survey period in 2023.

The geomorphic features the west-coast lakes contribute to extensive periods of thermal stratification and subsequent deoxygenation of the hypolimnetic zone. However, low external phosphorus loading from the catchment means that the pool of TP in the sediment is likely restricted and phosphorus release rates are likely lower in comparison to lakes with more extensive catchments and permanent inflows. Given the low phosphorus loading, nitrogen is likely the dominant nutrient in these lakes, as ammonium and nitrate move more freely as solutes in groundwater (Hamilton et al. 2018). The three Ngāroto Lakes on the east coast are shallower, polymictic and have more extensive catchments for the size of the lake. However, both phosphorus and nitrogen internal loading appears to be lower than would be expected in other shallow eutrophic New Zealand lakes. The distinct stratification patterns, external and internal nutrient loading rates of these dune lakes should be accounted for when developing effective ecological models for management purposes.

Conclusions

- Littoral groundwater infiltration rates and sediment nutrient release rates were investigated in seven dune lakes (Kawaupaku, Ōkaihau, Te Kanae, Spectacle, Slipper, Tomarata and Whatihua) located in the Auckland region. Lake levels were significantly elevated above the mean due to the higher-than-normal rainfall during 2023 which likely elevated littoral groundwater infiltration rates and no net efflux was detected at any of the sites. However, infiltration rates were within the range reported in

comparative studies and likely represent a significant proportion of hydrological inflow to the lakes.

- Sediment nutrient flux rates could only be determined for lakes Spectacle, Slipper and Tomarata using benthic chambers. However, sediment nutrient release rates were comparatively modest compared to those reported in similar studies, particularly in Lake Tomarata. Both internal and external phosphorus loading appears to be limited, while nitrogen loading appears to be driven by both groundwater and internal sediment release under changing redox conditions. These findings highlight the processes driving nitrogen and phosphorus loading in the lakes studied and provides data critical for the parameterisation of future water quality models.

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Appendices

Appendix 1. Location and deployment date of littoral groundwater infiltration chambers.

Chamber ID	Longitude	Latitude	Winter deployment	Spring deployment
Kawaupaku 1	174.456712	-36.894117	12/07/2023	No suitable site
Ōkaihau 1	174.438327	-36.80849	No access to lake	13/11/2023
Ōkaihau 2	174.440259	-36.810469	No access to lake	13/11/2023
Ōkaihau 3	174.439964	-36.807995	No access to lake	13/11/2023
Te Kanae 1	174.287166	-36.578403	8/06/2023	21/11/2023
Te Kanae 2	174.289813	-36.575381	8/06/2023	21/11/2023
Te Kanae 3	174.287416	-36.579331	8/06/2023	21/11/2023
Whatihua 1	174.671504	-37.275266	9/06/2023	8/11/2023
Whatihua 2	174.668734	-37.275509	9/06/2023	8/11/2023
Whatihua 3	174.668654	-37.276075	9/06/2023	8/11/2023
Slipper 1	174.633828	-36.171258	15/06/2023	30/10/2023
Spectacle 1	174.629806	-36.175898	15/06/2023	3/11/2023
Spectacle 2	174.626594	-36.1798	15/06/2023	3/11/2023
Tomarata 1	174.647447	-36.191885	22/08/2023	1/11/2023
Tomarata 2	174.647941	-36.191534	22/08/2023	1/11/2023
Tomarata 3	174.650933	-36.192307	22/08/2023	1/11/2023
Tomarata 4	174.651724	-36.192884	22/08/2023	1/11/2023

Appendix 2. Geomorphological characteristics of investigated dune lakes (FENZ 2024).

Lake	Max depth (m)	Lake area (ha)	Lake volume (m ³)	Lake surface area: volume	Catchment area (ha)	Catchment area: Lake surface area
Te Kanae	23.0	5.6	429,679	0.130	42.1	7.5
Kawaupaku	21.4	10.5	830,350	0.126	102.3	9.7
Ōkaihau	11.3	6.3	214,228	0.296	100.0	15.9
Whatihua	11.0	3.4	92,672	0.367	105.9	31.1
Spectacle	5.5	39.6	1,023,020	0.387	369.0	9.3
Slipper	5.4	8.8	193,220	0.454	675.6	76.8*
Tomarata	5.2	14.4	239,265	0.602	94.9	6.6

* Spectacle Lake flows into Slipper Lake

Appendix 3. Daily dissolved oxygen 1 m above the sediment in (A) Lake Kawaupaku, (B) Lake Ōkaihau, (C) lake Whatihua from fixed string monitoring data for the 2022-2023 period (C. McBride, Limnotrack).

