

Sediment Aluminium Content of Lakes Rotorua and Rotoehu: 2024 Monitoring Survey



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Executive Summary

Continuous alum (aluminium sulphate) dosing of the Utuhina Stream was initiated in 2006, with the objective of reducing dissolved reactive phosphate (DRP) loading of Lake Rotorua, thereby reducing lake primary productivity. A second continuous alum dosing station began operation on the Puarenga Stream in 2010. The water quality of Lake Rotorua has improved, with the Trophic Lake Index (TLI) declining from 5.0 in 2004 to 4.3 in 2024. Similarly, continuous alum dosing of the Waitangi Stream which flows into Lake Rotoehu began in 2011. However, alum dosing at this site was not as effective as anticipated, as invasive aquatic weed inhibited alum from reaching the main basin. As of 31 December 2023, a total of 993 tonnes of aluminium had been dosed to Lake Rotorua and 128 tonnes to Lake Rotoehu.

The University of Waikato was contracted by the Bay of Plenty Regional Council to conduct ongoing monitoring of sediment aluminium content in lakes Rotorua and Rotoehu as part of the resource consent conditions for alum dosing of inflows to these lakes. In addition to sediment total aluminium content, the percentage of amorphous (non-crystalline) aluminium was determined. Amorphous aluminium is the fraction of total aluminium able to adsorb dissolved phosphorus, sequestering it from the water column. It was assumed that the amorphous aluminium primarily represented the alum-derived aluminium fraction of total aluminium and will decline over time as alum floc mineralises, given no new alum enters the system.

Fifteen sediment cores were taken from Lake Rotorua in January 2024. Mean sediment aluminium content for the main basin of Lake Rotorua (sites Ra9–15) remained unchanged comparatively to previous surveys at approximately 5 g Al kg⁻¹ dry weight. However, notable increases in mean sediment total aluminium content at the near shore sites east of Sulphur Bay (sites Ra2 and Ra3) were observed, with total aluminium content doubling from 2020 to 2024, although the percentage of amorphous aluminium remained similar to 2020 levels. In contrast, sites Ra6 and Ra7 to the west of Sulphur Bay had marked decreases in total aluminium of approximately 2–3 g Al kg⁻¹ DW in the surface (0–4 cm depth) sediment, although amorphous aluminium was still comparatively higher than any other sites, likely reflecting the sites' proximity to the Utuhina Stream. Site Ra5, located in the deep (45 m) volcanic crater off Motutara Point, exhibited the most substantive reductions in sediment aluminium content with mean core total aluminium reduced by approximately 40% (3.2 g Al kg⁻¹ DW) and the percentage of amorphous aluminium halved compared to the 2020 survey.

The changes in sediment aluminium content at near-shore sites may reflect periodic resuspension and redistribution of sediment alum floc during storm events, such as cyclone Gabrielle. However, this is unlikely to explain the changes observed at sites in the deeper volcanic area north of Motutara Point (sites Ra5 and Ra 8). It is possible that the changes in

sediment aluminium content in this area may be due to hydrothermal activity at the northern boundary of the Rotorua geothermal field. Given the periodic resuspension of alum floc in the near-shore environment of Lake Rotorua, coupled with static total aluminium levels in the main basin of the lake, there remains some uncertainty regarding the fate and transport pathways of alum-derived aluminium in Lake Rotorua. Hydrodynamic modelling of alum floc discharged from the Utuhina Stream coupled with resuspension during storm events could assist in understanding the effectiveness and fate of alum-derived aluminium in Lake Rotorua.

Alum dosing to Lake Rotoehu has been minimal between 2018 and 2023, with low-level dosing only occurring over a 9-month period over 2021–2022. Seven sites were surveyed in January 2024, extending from the mouth of the Waitangi Stream out into the main basin of the lake. There were no substantive changes in sediment total aluminium with sediment aluminium content approximately 5-6 g Al kg⁻¹ DW in the main basin of the lake (sites Rh4–7). However, the percentage of amorphous aluminium had declined markedly at all sites, particularly near the discharge point of the Waitangi Stream at Te Wairoa Bay (sites Rh1–2), where amorphous aluminium in the surface sediment declined from approximately 100% in 2016 to <20% in 2024. This reduction in amorphous aluminium likely represents natural mineralisation of alum-derived aluminium. While legacy accumulation of total aluminium can still be observed, it is unlikely to result in ecological impacts due to its inert nature.

Recommendations

1. On-going sediment monitoring for alum-derived aluminium should incorporate quantification of both total and amorphous aluminium as it provides additional insights to the origin and age of sediment aluminium.
2. Unless alum dosing is resumed, further sediment aluminium surveys of Lake Rotoehu are unlikely to provide substantive insights.
3. Consideration should be given to hydrological modelling of alum floc including storm event scenarios. When coupled with a mass balance budget of alum-derived aluminium, this will provide an improved understanding of the fate of aluminium in Lake Rotorua.

Acknowledgements

I would like to thank Deniz Özkundakci for reviewing this document. Joe Butterworth and Warrick Powrie provided field support. ICP-MS analysis was conducted by Danielle Blackwell. Additional support and funding were provided by the Bay of Plenty Regional Council Chair in Lakes and Freshwater Science.

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Introduction

Alum (aluminium sulphate) dosing is widely used for lake restoration and is intended to sequester dissolved reactive phosphate (DRP), thereby reducing phytoplankton growth and improving water clarity (Cooke et al. 2005). When added to water, alum forms aluminium hydroxide ($\text{Al}(\text{OH})_3$) which adsorbs dissolved phosphorus and coagulates suspended particles (Cooke et al. 2005). The resulting aluminium floc may either be lost from the system through outflows or settle to the bottom sediment. In deeper lakes, it may form a sediment capping layer, adsorbing phosphate released from sediment under hypoxic reducing conditions (Welch and Cooke 1999; Egemose et al. 2013). In shallow lakes or lake margins, it may be subjected to wind-driven resuspension, causing settled flocs to be transported to deeper parts of the lake or discharged from the lake (Cooke et al. 2005). Once settled, alum floc undergoes an aging process, changing from a colloidal amorphous solid to microcrystals, and then to the mineral gibbsite in a process that may take up to a year (Cooke et al. 2005).

Near continuous alum dosing of the Utuhina and Puarenga inflows to Lake Rotorua has been conducted by the Bay of Plenty Regional Council since 2006 and 2010, respectively. Dosing to the Puarenga Stream was halted from 30 September 2018 to 22 November 2020 for plant upgrades, and all dosing was halted for approximately 2 months in 2022 due to COVID-19 restrictions. Continuous alum dosing of the Waitangi Stream which flows into Lake Rotoehu was initiated in 2011, however dosing was halted from July 2018 to December 2020 due to concerns about invasive aquatic weed interference with alum delivery to the lake. Dosing was restarted in December 2020 but was again halted after 9 months in 2021 for system maintenance. However, dosing was not restarted due to high lake levels raising the water levels in the Waitangi Stream and flooding the alum dosing station in 2023. Total daily aluminium dose rates and annual trophic lake index (TLI) for lakes Rotorua and Rotoehu are presented in Figure 1. As of 31 December 2023, a total of 993 tonnes of aluminium had been dosed to Lake Rotorua and 128 tonnes to Lake Rotoehu.

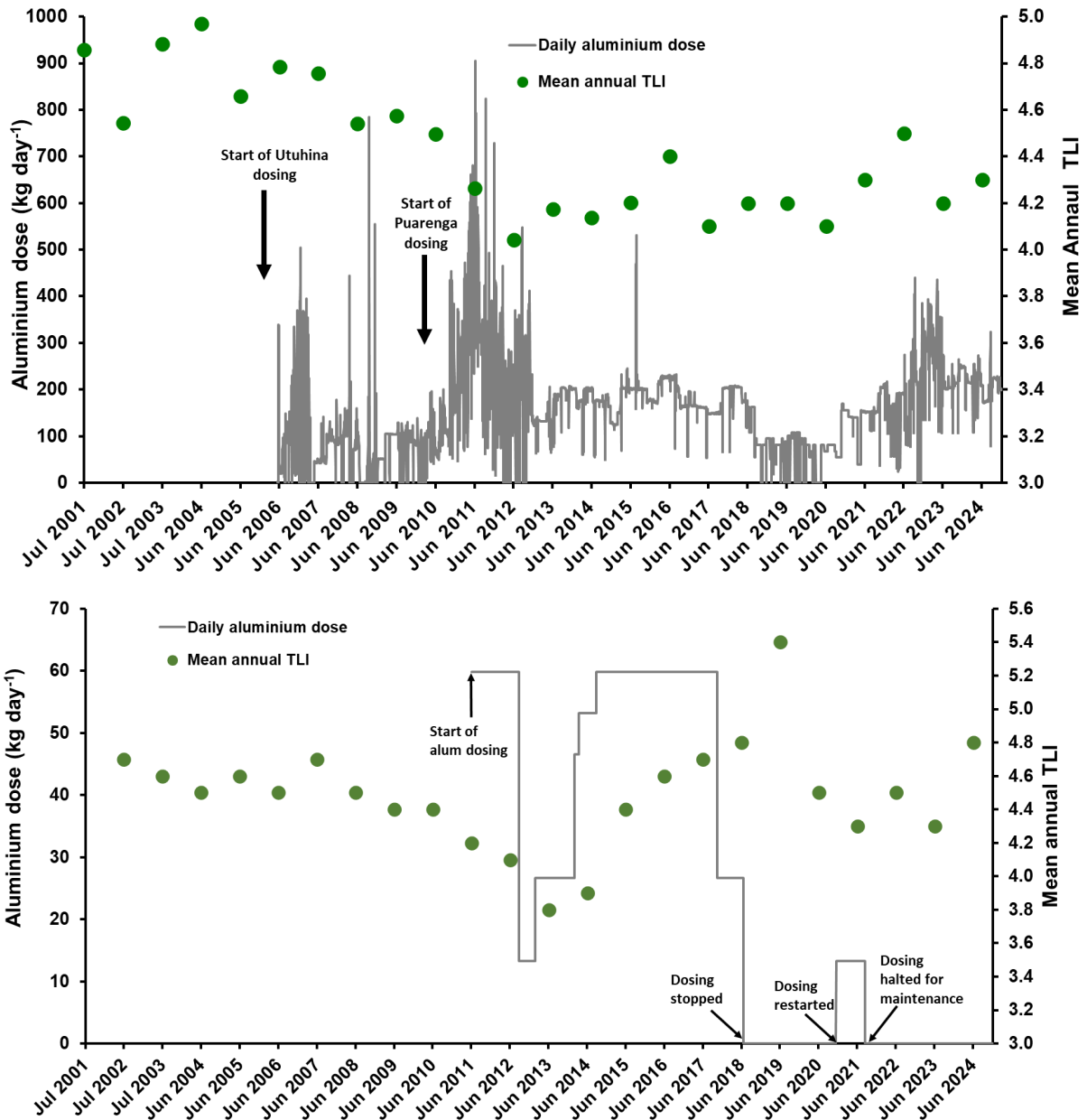


Figure 1. Daily aluminium dose rates to Lake Rotorua (top) and Lake Rotoehu (bottom) with mean annual Trophic Level Index (TLI) from 2001 to 2024.

Previous sediment surveys of Lake Rotorua were conducted prior to alum dosing (Pearson 2007), and following initiation of alum dosing of the inflows (Özkundakci et al. 2013; Tempero and Hamilton 2016; Tempero 2019; Tempero and Davies-Calway 2021). Post-alum dosing surveys initially focused on the main basin of Lake Rotorua, with sediment coring sites all below 10 m depth, with no significant increases in surface (0–4 cm) sediment total aluminium concentrations detected compared to pre-alum dosing (Özkundakci et al. 2013; Tempero and Hamilton 2016). However, Tempero and Hamilton (2016) did report increases in the amount of surface sediment amorphous (i.e., primarily alum-derived) aluminium at core sites closest

to the Utuhina and Puarenga inflows, indicating the recent deposition of alum floc. In 2019, a follow up survey of the near-shore environment at depths of 4-5 m along the southern perimeter of the lake found substantial accumulations of amorphous aluminium proximate to the discharge point of the Utuhina Stream between Kawaha Point and Motutara Point, including the deep (45 m) volcanic crater off Motutara Point (Tempero 2019). In contrast, cores taken to the east of Sulphur Bay showed little or no accumulation of amorphous aluminium, which was attributed to wave resuspension of alum floc in this area (Tempero 2019). A full sediment survey of Lake Rotorua incorporating the near-shore sites was conducted in December 2020 and produced similar findings to previous surveys. There was little evidence for aluminium accumulation in the main basin of the lake, with amorphous aluminium primarily occurring in near the discharge point of the Utuhina Stream and Sulphur Bay (the discharge point of the Puarenga Stream) (Tempero and Davies-Calway 2021). It was also suggested that extensive beds of *Lagarosiphon major*, up to several meters in height in Te Ruapeka Bay to the west of Sulphur Bay may have a dampening effect on wave resuspension of alum floc, preventing it from reaching the main basin of the lake (Tempero 2019; Tempero and Davies-Calway 2021). It was concluded that alum derived aluminium from the Utuhina and Puarenga Streams was not accumulating in the main basin of Lake Rotorua but was either being deposited in the nearshore zone (<10 m depth) or remained in suspension and discharged from the lake (Tempero and Davies-Calway 2021).

Sediment aluminium content surveys of Lake Rotoehu have been conducted by Tempero and Hamilton (2016) and Tempero and Davies-Calway (2021). Significant accumulation of alum-derived aluminium was found in Te Wairoa Bay, at the discharge point of the Waitangi Stream. However, no observable accumulation of aluminium was found in the main basin of Lake Rotoehu. It was suggested that impedance of stream flow and dampening of wave resuspension by extensive *Ceratophyllum demersum* weed beds in Te Wairoa Bay prevented alum floc from being transported to the main basin of the lake (Tempero and Hamilton 2016; Eager 2017).

Sediment aluminium surveys of lakes Rotorua and Rotoehu were conducted to monitor sediment aluminium accumulation as part of the Bay of Plenty Regional Council's resource consent for alum dosing. In Lake Rotorua, sediment cores were taken from 15 sites previously surveyed by Tempero and Davies-Calway (2021). Additionally, seven sites were cored at Lake Rotoehu at locations initially sampled by Tempero and Hamilton (2016). Sediment cores were sectioned and analysed for total and non-crystalline aluminium content by inductively coupled plasma mass spectrometry (ICP-MS) to determine alum-derived aluminium content.

Methods

Site descriptions

Lake Rotorua is the largest of 12 lakes jointly managed under the Rotorua Te Arawa Lakes Programme. It has a surface area of 80.6 km², a mean depth of 10.8 m (maximum depth 45 m), a total water volume of 0.85 km³ and polymictic stratification patterns (Burger et al. 2011). Lake Rotorua is currently classified as eutrophic but has experienced significant improvements water quality since the mid-2000s, with the TLI fluctuating around the target TLI of 4.2 since 2012 (BoPRC monitoring data). Alum is currently dosed to the Utuhina and Puarenga inflows as they pass through Rotorua City. The lake drains by way of the Ōhau Channel to Lake Rotoiti and the Kaituna River.

Lake Rotoehu is a shallow (mean depth 8.2 m; maximum depth 13.5 m), moderately sized (7.9 km²), polymictic lake in the Te Arawa lakes district (Scholes 2009). Geothermal waters contribute dissolved nitrogen and phosphorus to the lake, which has been classified as eutrophic for > 30 years (Woelmer et al. 2025). Analysis of water quality drivers indicates that alum dosing appears to have had a limited impact on water quality, with lake water level and climatic factors being the key drivers of TLI levels (Woelmer et al. 2025). Lake Rotoehu is primarily fed by groundwater discharge and often experiences large fluctuations in water levels, and at the time of sampling the lake level was approximately 2 m above its mean height after reaching near-record high in mid-2023.

Sediment survey locations

Based on the recommendations of Tempero (2019) to increase the number of near-shore monitoring sites, 15 coring sites were selected for Lake Rotorua, including seven nearshore sites (Ra1–7) and eight main basin core locations (Ra8–15) (Figure 2; Appendix 1). Sampling was conducted on 22nd and 23rd January 2024, site coordinates and water depth at coring sites are provided in Appendix 1.

Seven sediment cores were taken from Lake Rotoehu on 31 January 2024 at the same locations sampled by (Tempero and Hamilton 2016) (Figure 3). Coring sites were chosen to represent a likely gradient of sediment aluminium concentrations running from high levels where the alum dosed Waitangi Springs Stream enters the lake at Te Wairoa Bay, extending out into the in the main basin. Lake Rotoehu coring site coordinates are provided in Appendix 2.

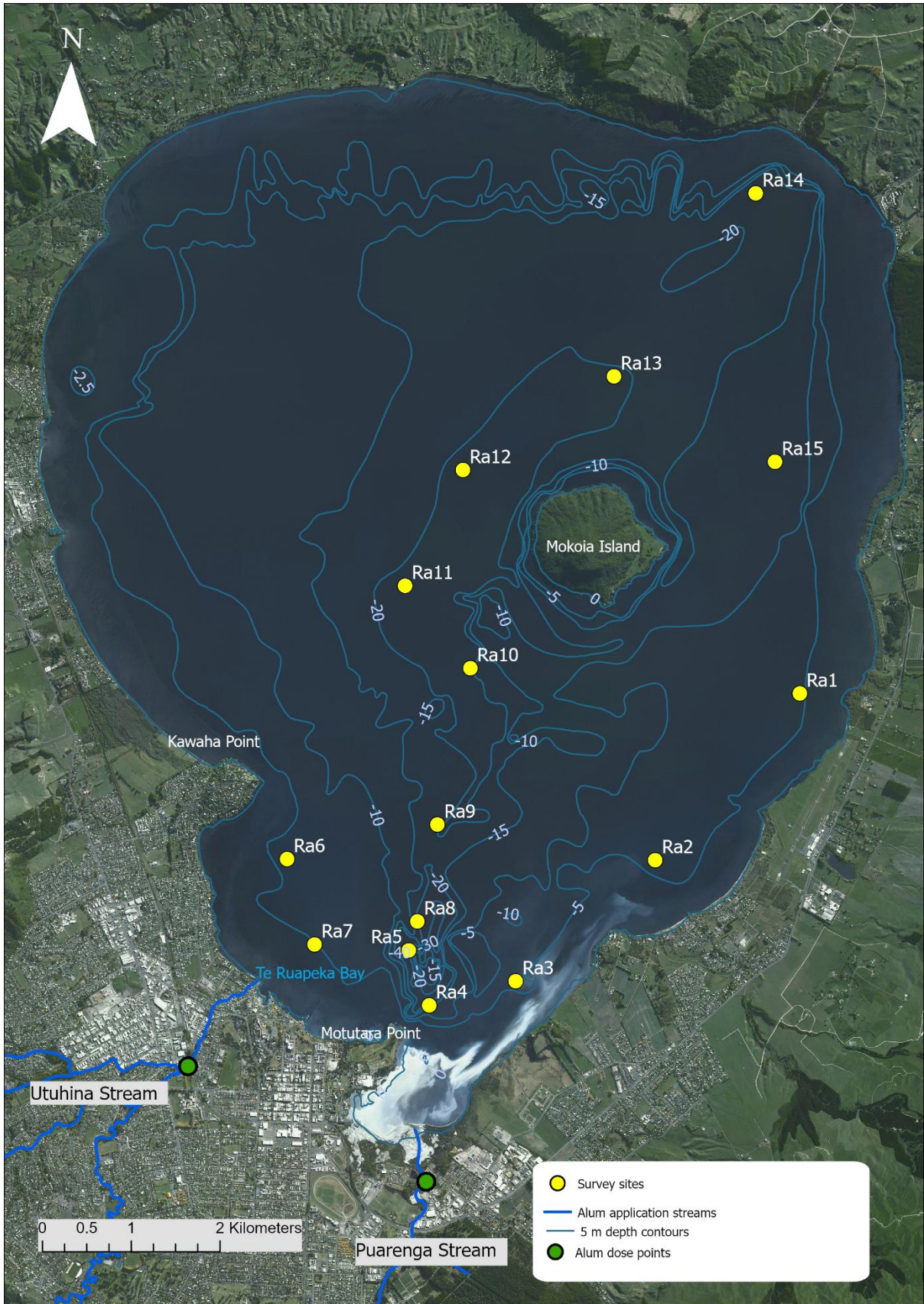


Figure 2. Locations of sediment cores (Ra1–15) taken from Lake Rotorua on 22 and 23 January 2024.

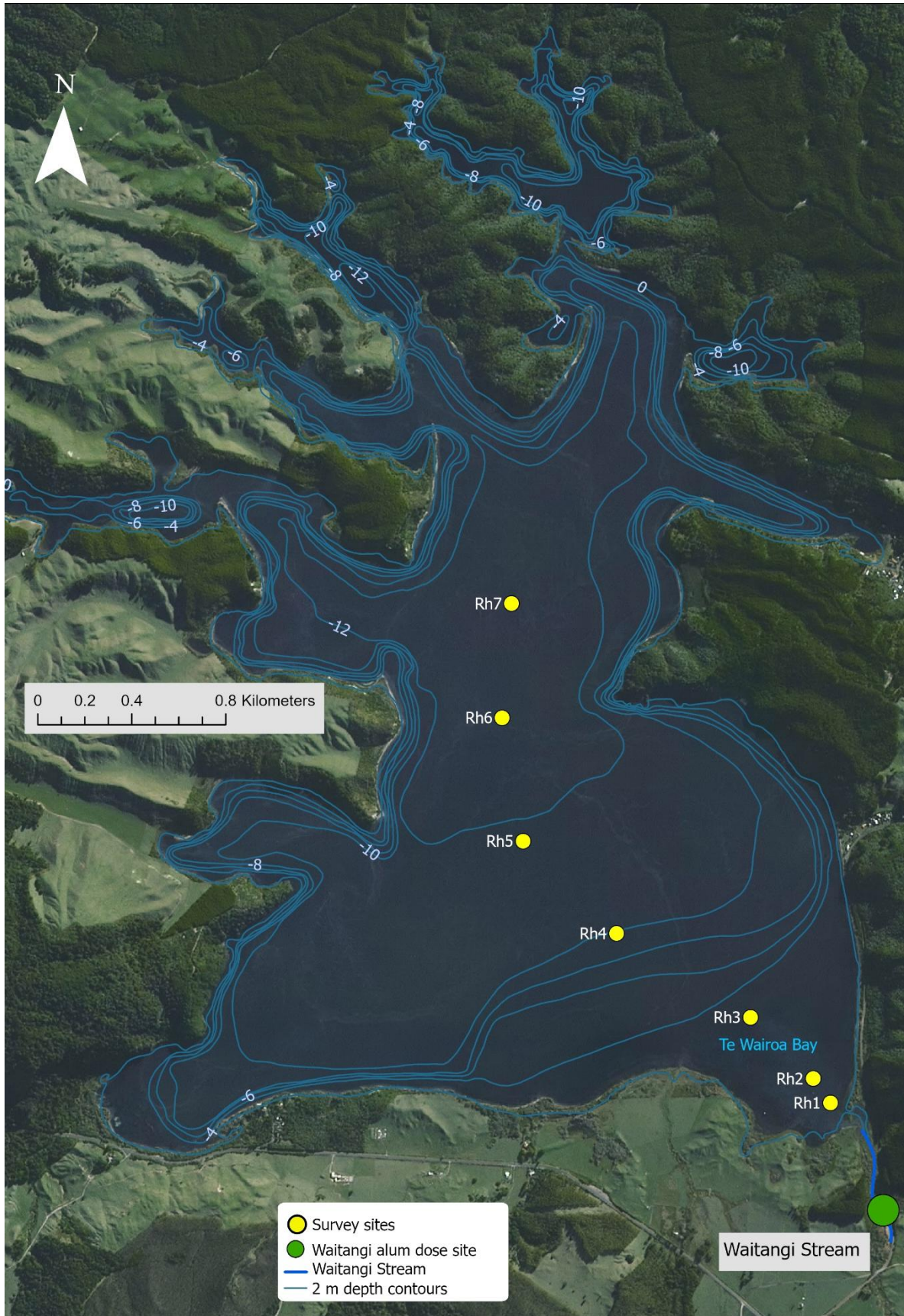


Figure 3. Lake Rotoehu sediment core sites (Rh1-7) sampled on 31 January 2024.

Sediment core retrieval and processing

Sediment cores were collected using a gravity corer (Pylonex HTH 70 mm) with a 60 x 600 mm Perspex (Plexiglas) core barrel to capture undisturbed sediments. The core was extruded by a piston from the base and excess supernatant water allowed to overflow from the top of the barrel upon extrusion until the sediment-water interface was exposed. Sediment samples were extruded at 1-cm vertical intervals up to 4 cm sediment depth and transferred into 50 mL polypropylene centrifuge tubes. From 4 to 20 cm depth, the sediment was sectioned at 2-cm intervals. Sediment samples were stored on ice until analysis in the laboratory. In Lake Rotorua, the sediment composition at coring sites Ra1, Ra2, Ra3, Ra6 and Ra7 was primarily coarse gravel and sand, with dense beds of *L. major* at sites Ra6 and Ra7. This necessitated the use of a scuba diver to push the corer barrel into the sediment, then retrieving the intact sediment core.

Sediment analysis

Sectioned sediment samples were dried at 60°C for 7 days and then lightly ground using a mortar and pestle. Sediment total aluminium content was determined by reverse aqua regia digestion. Sediment samples (0.1 g) were left to pre-digest overnight at room temperature following the addition of 1 mL concentrated nitric acid and 0.33 mL concentrated hydrochloric acid. Samples were then digested at 80°C for 1 hour in a circulating water bath, followed by the addition of 50 mL ultrapure water. The samples were then centrifuged and 15 mL of supernatant filtered using 0.2 µm cellulose acetate filters (Satorius, Germany). Samples and control blanks were then analysed for aluminium content using inductively coupled plasma mass spectrometry (ICP-MS; model Agilent 8900 with a triple-quadrupole).

Sediment non-crystalline (amorphous) aluminium was determined by ammonium oxalate digestion using a modified method described in Hodges and Zelazny (1980). Sediment (0.2 g) was shaken with 50 mL 0.2 N ammonium oxalate (Sigma, Australia) (pH 3) for 2 hours in the dark, followed by centrifugation for 5 minutes at 5000 rpm. The supernatant was then filtered using 0.2 µm cellulose acetate filters and aluminium content determined by ICP-MS.

Results

Lake Rotorua

Core composition

Following retrieval, the sediment cores were visually inspected, with what appeared to be alum floc at the sediment-water interface at near-shore sites Ra2 and Ra3 (Appendix 3). No alum floc was evident at the deeper (Ra9–Ra15) sites and no distinguishing tephra layers were observed to assist with dating. At sites Ra1–3, the top 0–12 cm of sediment was composed primarily of gravel and coarse sand to transitioning finer sand and silt below 12 cm depth. Cores from sites Ra3, Ra6 and Ra7 also contained small fragments of vegetative material, likely derived from the *L. major* beds in these areas. Cores sampled from the deeper sites in the lake were composed of silt and clay particles and were free from vegetation.

Sediment total aluminium content

There were small declines in sediment mean total aluminium content in the main basin (i.e., sites Ra9–Ra15) of Lake Rotorua between 2020 and 2024, with mean aluminium content ranging from 4.9–5.8 g Al kg⁻¹ dry weight (DW) in 2020 and 4.7–5.2 g Al kg⁻¹ DW in 2024. In comparison, differences in mean aluminium content were observed in the shallower (5 m depth) near-shore sites (Ra1–Ra4, Ra6, Ra7) and the volcanic crater off Motutara Point (Ra5 and Ra 8). This included increases in mean total aluminium from 1.3 to 2.5 g Al kg⁻¹ DW at site Ra2, and 2.2 to 4.9 g Al kg⁻¹ DW at site Ra3. In comparison, mean core aluminium content at the crater sites decreased from 10.0 g Al kg⁻¹ DW in 2019 to 4.9 g Al kg⁻¹ DW in 2024 at site Ra5 and site Ra8 declined from 8.6 to 4.9 g Al kg⁻¹ DW between 2020 and 2024 (Figure 4).

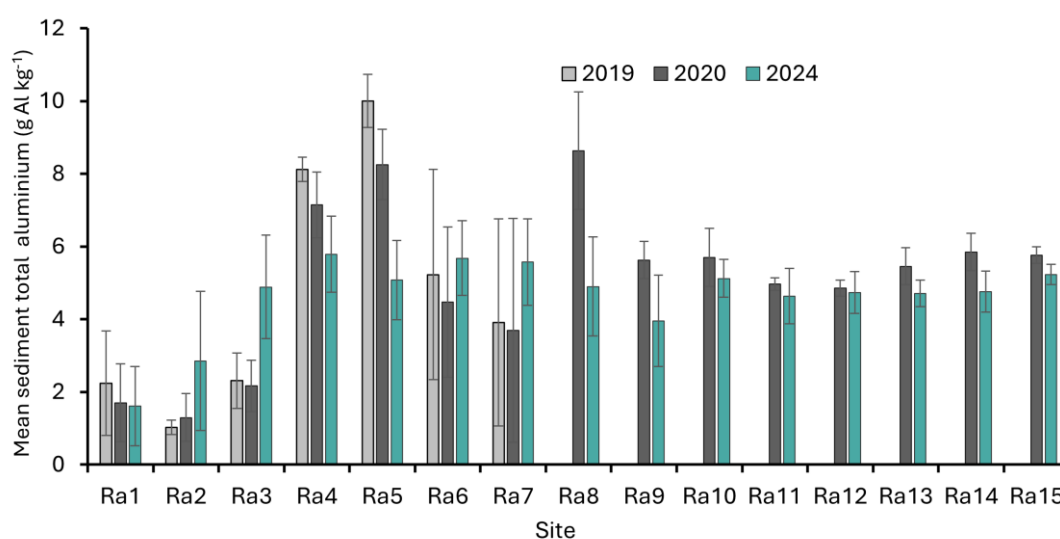


Figure 4. Lake Rotorua sediment core (0–20 cm depth) mean (± 1 standard deviation) total aluminium content for years 2019, 2020 and 2024. Note: sites Ra8–Ra15 were not surveyed in 2019.

Differences in sediment core total aluminium content were largely driven by changes in surface (0–4 cm depth) sediment aluminium concentrations (Appendix 4). Compared to the 2019 and 2020 surveys, there were notable differences in sediment aluminium content at Sites Ra1–3, located to the east of Sulphur Bay (Figure 5). Mean surface sediment total aluminium content was approximately 2–3 times (i.e., 3–6 g Al kg⁻¹ sediment dry weight) greater at sites Ra2 and Ra3 compared to the 2019 and 2020 surveys, although the proportion of amorphous aluminium was similar to that observed in previous surveys (Figure 6). However, site Ra1 showed no appreciable change in the vertical profile of total aluminium, but there was a substantial peak in amorphous aluminium in the deeper section (>14 cm depth) of the core (Figure 6).

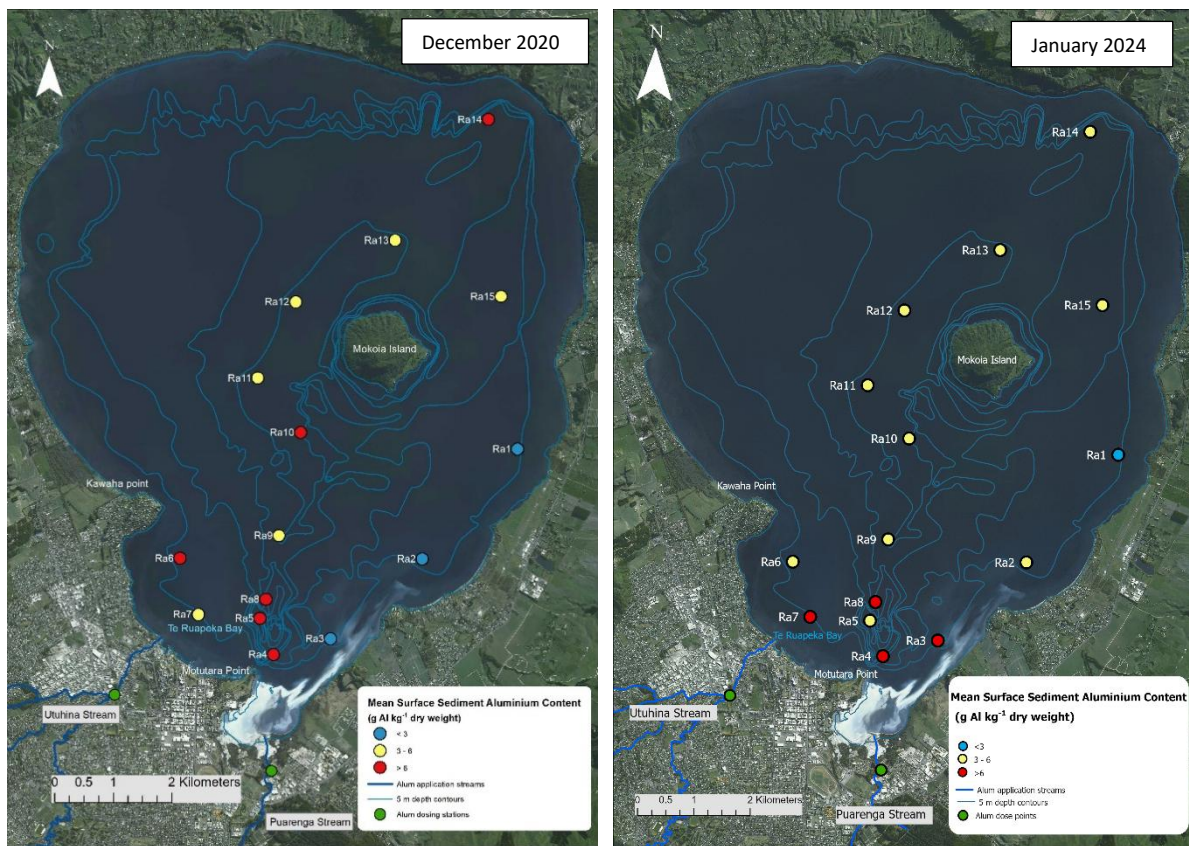


Figure 5. Comparative geographic distribution of mean surface (1–4 cm depth) sediment total aluminium content observed in surveys of Lake Rotorua in December 2020 (left) and the January 2024 (right).

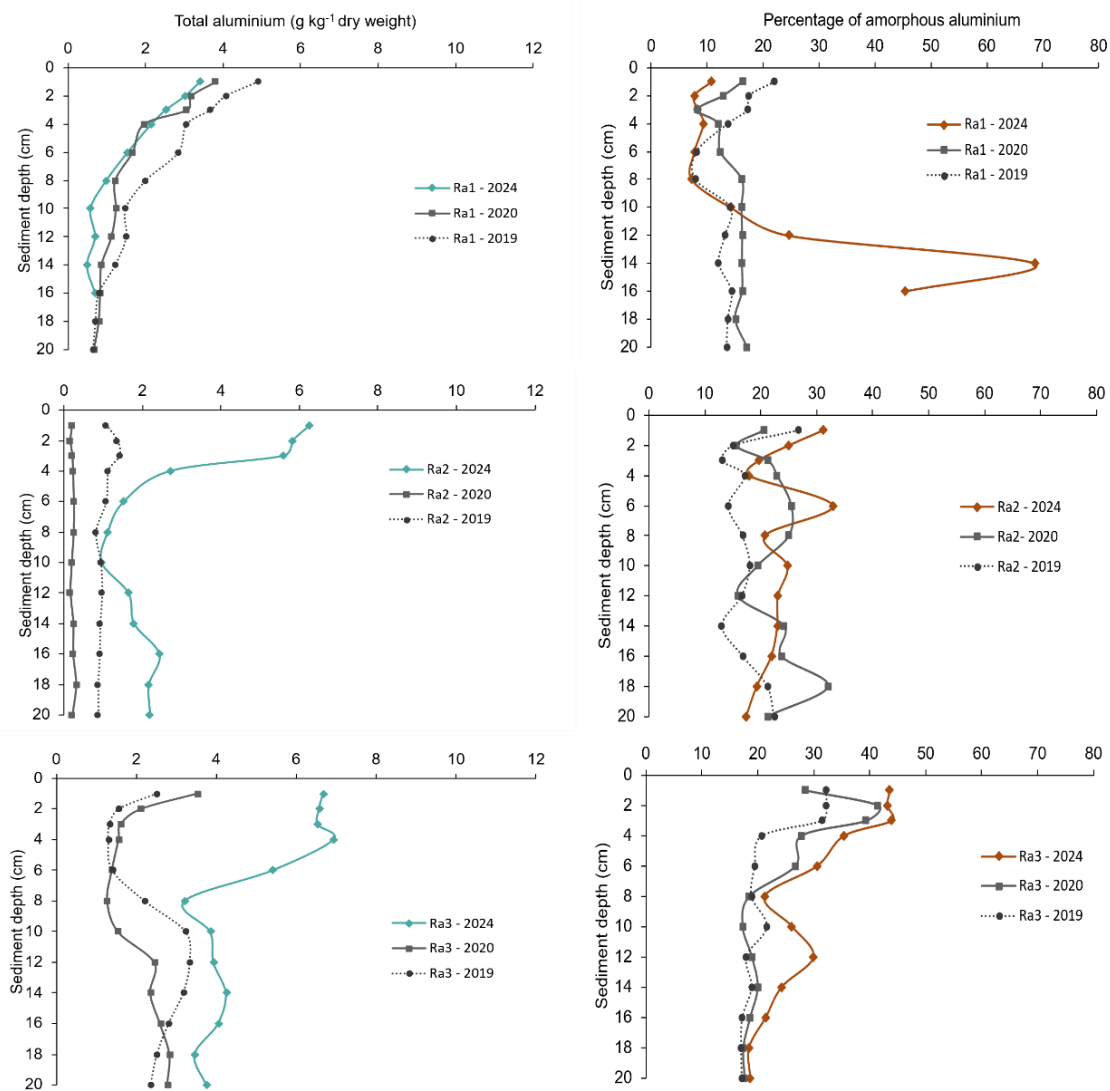


Figure 6. Vertical profiles of Lake Rotorua sites Ra1, Ra2 and Ra3 sediment total aluminium content (left) and percentage of amorphous (non-crystalline) aluminium (right) from January 2024 with comparisons to 2019 December and 2020 survey data.

When compared to the 2019 and 2020 surveys, notable declines in both total aluminium and the percentage of amorphous aluminium were observed at sites Ra4–Ra7, either in the surface sediments (i.e., Ra7) or throughout the sediment profiles (i.e., Ra5) (Figure 7). Site Ra5, located in the deep (45 m) volcanic crater off Motutara Point, exhibited a moderate reduction in sediment aluminium content, with mean core total aluminium reduced by 3.2 g Al kg⁻¹ and the percentage of amorphous aluminium reduced to half that observed in 2020 (Figure 7). In addition, surface sediment peaks in total aluminium previously observed at sites Ra6 and Ra7 were no longer present, with total aluminium now more uniformly distributed through the sediment core profile. The amount of amorphous aluminium in the surface sediments at sites Ra6 and Ra7 was similar to previous surveys (i.e., ~40%) but substantially declined lower in the sediment profile compared to previous surveys. Site Ra4 exhibited

changes in aluminium content in comparison to previous surveys, however, sediment aluminium concentrations have been highly variable at this site, making it difficult to distinguish any patterns in aluminium distribution over time (Figure 7).

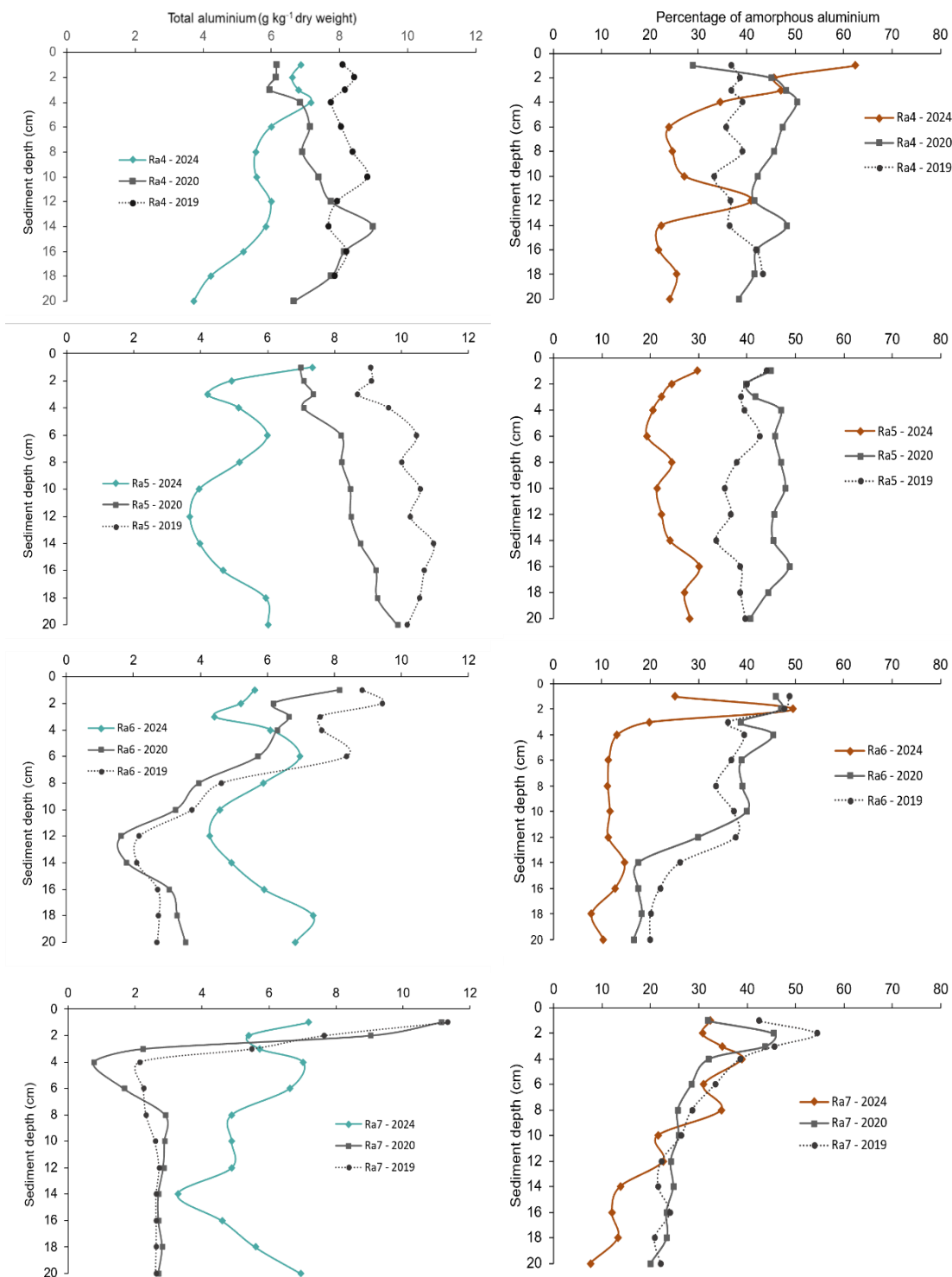


Figure 7. Vertical profiles of Lake Rotorua sites Ra4, Ra5, Ra6 and Ra7 sediment total aluminium content (left) and percentage of amorphous (non-crystalline) aluminium (right) from January 2024 with comparisons to 2019 and 2020 survey data.

Sediment profiles of total and amorphous aluminium at sites Ra8 and Ra9 have been highly variable over time, with sediment mean total aluminium declining substantially since the 2020 survey (Figure 4, Figure 8). In comparison, sites Ra10 and Ra11 exhibited similar vertical distribution patterns between previous surveys, although the percentages of amorphous aluminium were lower (~30%) than compared to those observed (~50%) in 2020 (Figure 8).

At sites to the north of Mokoia Island (Ra12, Ra13, Ra 14 and Ra 15), sediment showed very little variation in both vertical distribution and total mean aluminium content between sites and years (Figure 4, Figure 9). There was some reduction in amorphous aluminium with increasing sediment depth at Site Ra15 (i.e., 50% at 2-4cm to 10% at 20cm), while the proportion of amorphous aluminium was relatively consistent with depth at sites Ra12–Ra14 (~30–40%), although levels had reduced from 45–50% in 2020 to 30–35% 2024 (Figure 9).

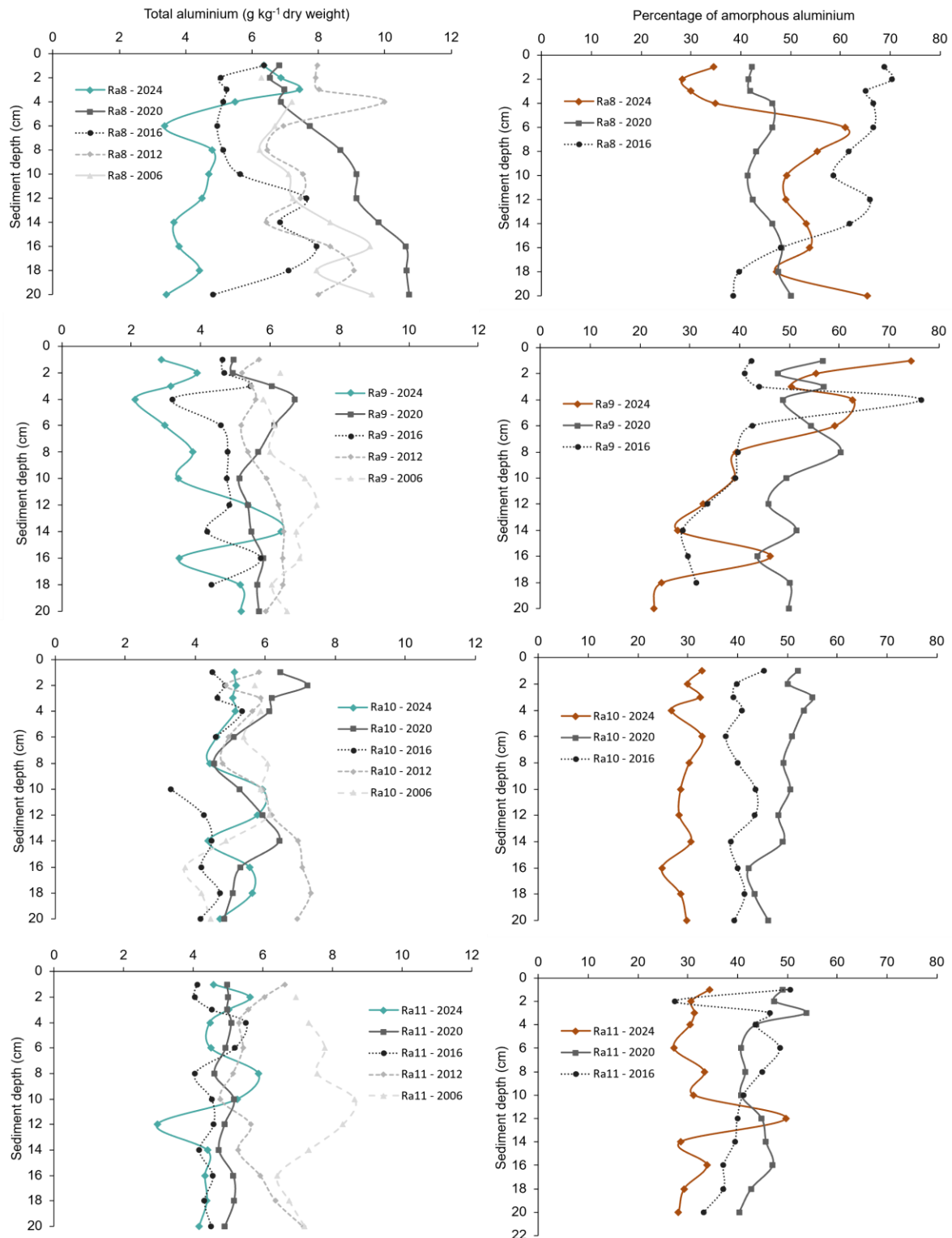


Figure 8. Vertical profiles of Lake Rotorua sites Ra8, Ra9, Ra10 and Ra11 sediment total aluminium content (left) and percentage of amorphous (non-crystalline) aluminium (right) from January 2024, with comparisons to surveys conducted in 2006, before the start of alum dosing, and subsequent surveys conducted in 2012, 2016 and 2020. Note: amorphous aluminium content has only been determined since 2016.

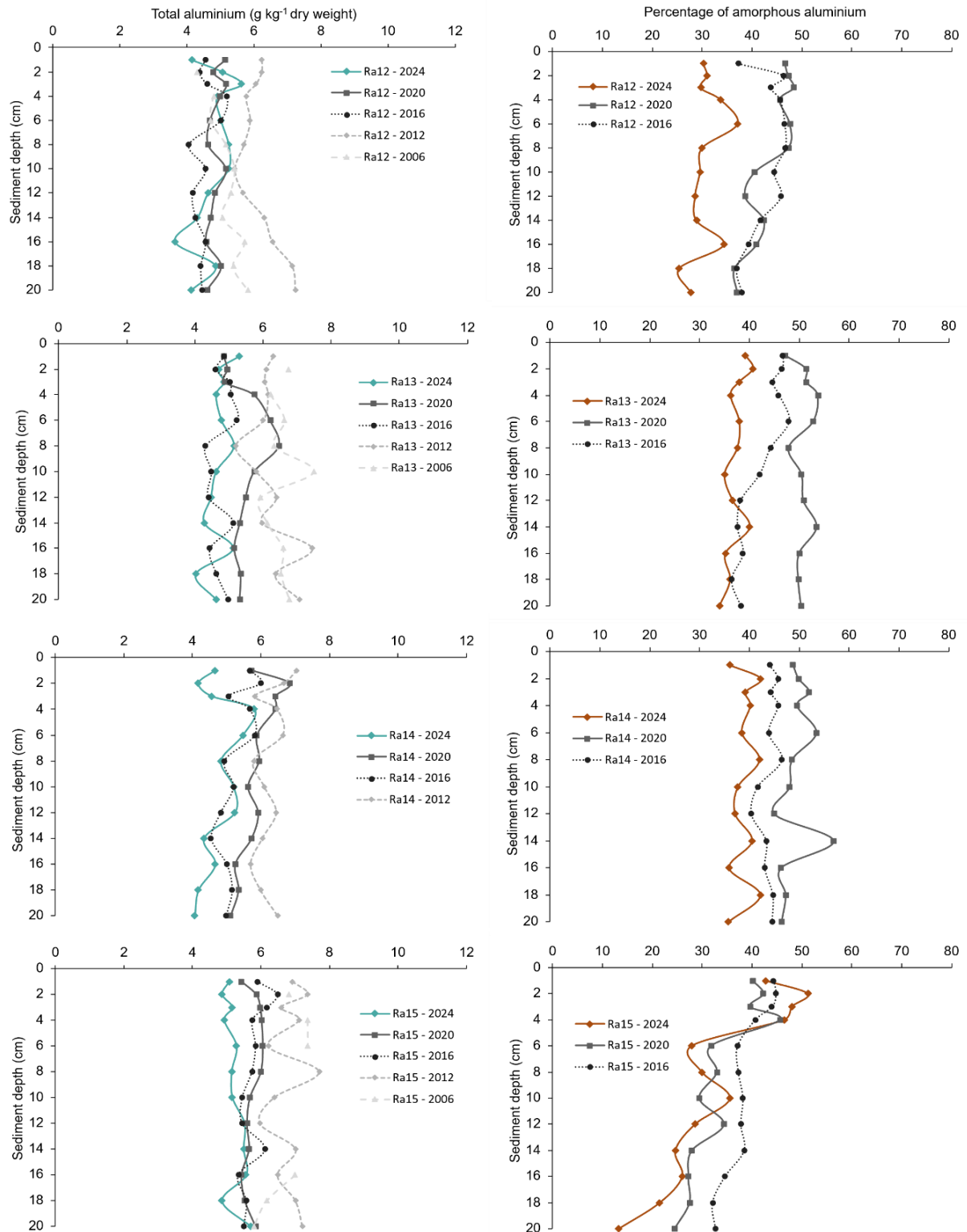


Figure 9. Vertical profiles of Lake Rotorua sites Ra12, Ra13, Ra14 and Ra15 sediment total aluminium content (left) and percentage of amorphous (non-crystalline) aluminium (right) from January 2024 with comparisons to surveys conducted in 2006, before the start of alum dosing, and subsequent surveys conducted in 2012, 2016 and 2020. Note: amorphous aluminium content has only been determined since 2016.

Lake Rotoehu

Core composition

The water level of Lake Rotoehu was approximately 0.5 m higher in compared to the previous sediment survey conducted December 2020, and 2.0 m higher than the February 2016 survey. Surface sediment from core sites Rh1 and Rh2 was composed of dark organic matter with decaying vegetation, primarily from hornwort (*Ceratophyllum demersum*). Deeper in the core (>10 cm depth) the sediment transitioned to fine sand, similar to that observed in core surface sediment during the 2016 survey. Cores taken from the main basin (sites Rh5–Rh7) of the lake were similar to those sampled in 2016 and 2020, composed of fine silt and occasional sand particles.

Sediment aluminium content

Mean sediment core total aluminium content in Lake Rotoehu was substantially higher at sites Rh1 and Rh2 (13.0 and 14.0 g Al kg⁻¹ DW, respectively) compared to the other Rotoehu sites (Rh3–7; range 4.9–5.7 g Al kg⁻¹ DW) (Figure 10). However, there was an increase in mean sediment aluminium concentrations at sites Rh3 and Rh4, with total aluminium increasing from ~2.5 g Al kg⁻¹ DW in 2016 to >4.8 g Al kg⁻¹ DW in 2024. Sites located at >10 m depth in the main basin (i.e., Rh5–Rh7) have had comparably consistent total aluminium levels between surveys, ranging from 5.0–5.5 g Al kg⁻¹ DW (Figure 10).

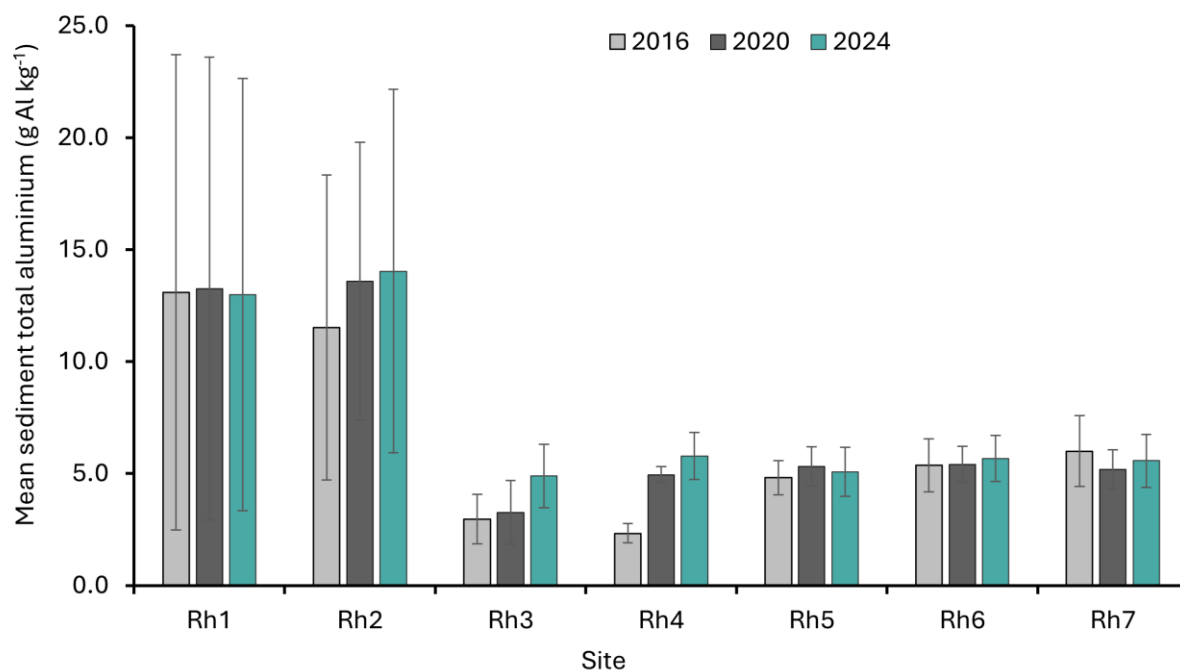


Figure 10. Lake Rotoehu sediment (0–20 cm depth) mean (± 1 standard deviation) total aluminium content for years 2016, 2020 and 2024.

At sites Rh3 to Rh7 surface sediment (0-4 cm depth) total aluminium concentrations have been generally consistent between surveys years and sites at $\sim 5 \text{ g Al kg}^{-1} \text{ DW}$ with site Rh4 having the greatest variation ranging from $2.6 \text{ g Al kg}^{-1} \text{ DW}$ in 2016 to $6.9 \text{ g Al kg}^{-1} \text{ DW}$ in 2024 (Appendix 5). In contrast, surface sediment total aluminium at site Rh2 declined from $15 \text{ g Al kg}^{-1} \text{ DW}$ in 2020 (c.f. $18 \text{ g Al kg}^{-1} \text{ DW}$ in 2016) to $5.2 \text{ g Al kg}^{-1} \text{ DW}$ in 2024. Vertical sediment profiles of aluminium content at Rh2 had peak aluminium concentrations at $\sim 14 \text{ cm}$ depth compared to 6 cm in 2020 and 2 cm in 2016 (Figure 11). Small increases ($\sim 2 \text{ g Al kg}^{-1} \text{ DW}$) in surface sediment aluminium content were also observed at sites Rh3 and Rh4 in 2024 compared to 2020 (Figure 11; Figure 12). Comparative spatial changes in surface sediment total aluminium content between 2020 and 2024 are presented in Appendix 5.

Appreciable reductions in the percentage of amorphous aluminium were observed in the 2024 survey, a continuing trend since amorphous aluminium was first quantified in 2016. The largest changes occurred at the sites closest to the Waitangi Stream discharge point (Rh1–Rh3) (Figure 11), where the percentage of amorphous aluminium in surface and middle (6–14 cm depth) sediment profiles had decreased from $\geq 70\%$ in 2016 to $< 20\%$ in 2024. Smaller decreases in amorphous aluminium were also evident in sediment cores Rh4–Rh7, with reductions of from approximately 40% to 20% between 2020 and 2024 (Figure 12).

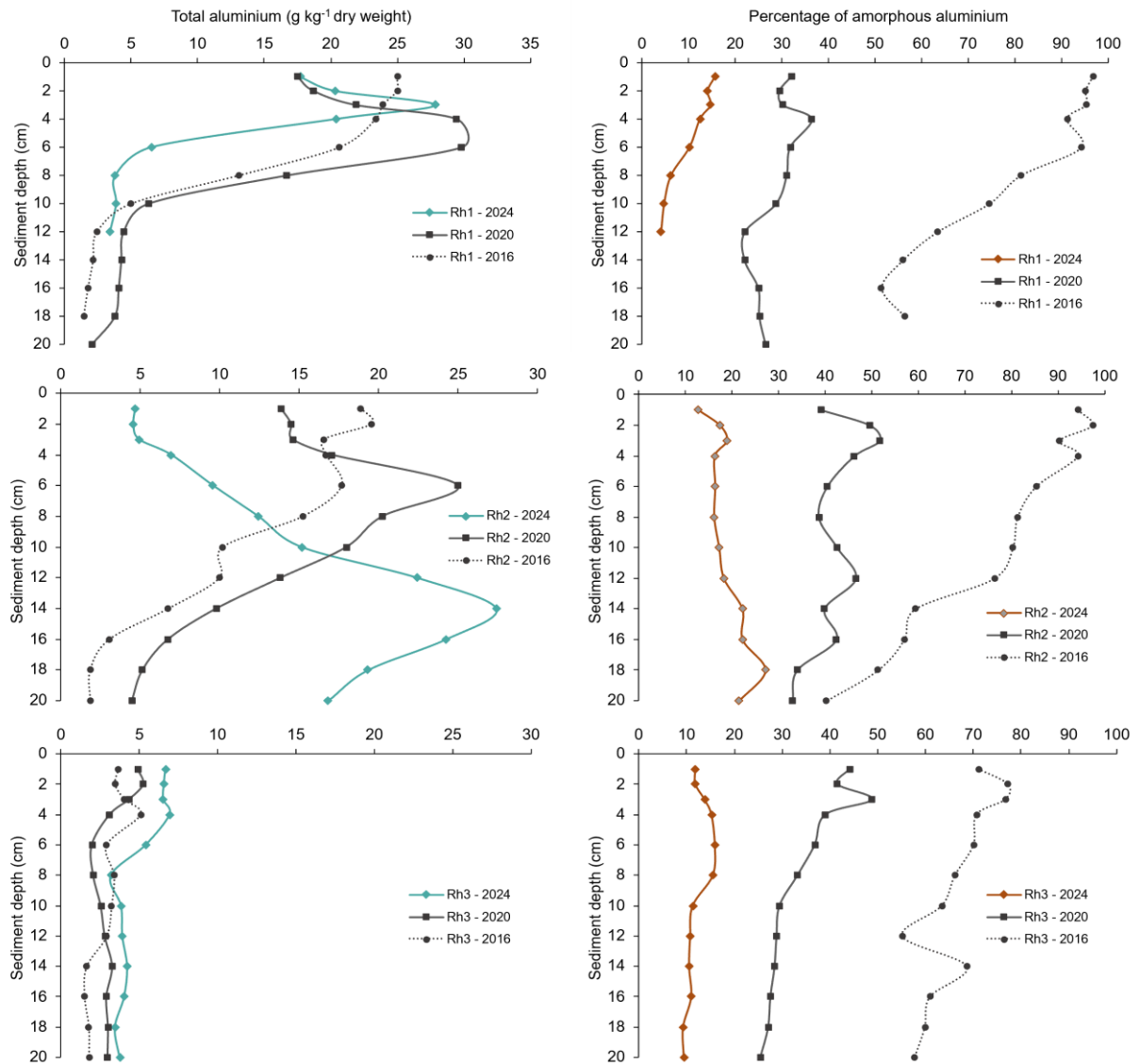


Figure 11. Vertical profiles of sediment total aluminium content (left) and percentage of amorphous (non-crystalline) aluminium from Lake Rotoehu sites Rh1, Rh2 and Rh3 from January 2024 with comparisons to 2020 and 2016 survey data.

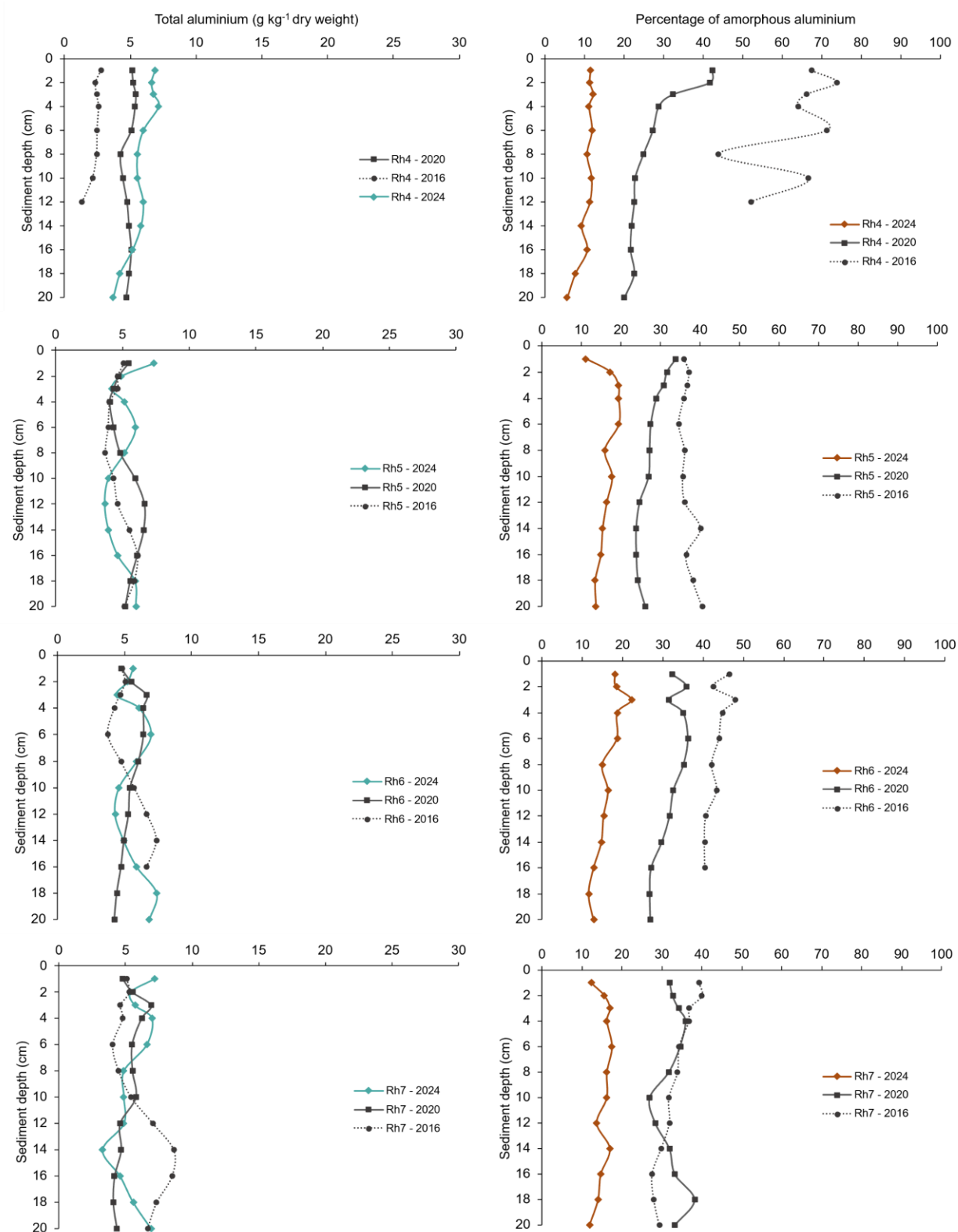


Figure 12. Vertical profiles of sediment total aluminium content (left) and percentage of amorphous (non-crystalline) aluminium from Lake Rotoehu sites Rh4, Rh5, Rh6 and Rh7 from January 2024 with comparisons to 2020 and 2016 survey data.

Discussion

Alum dosing of two inflows to Lake Rotorua between 2006 and 2023 has resulted in the cumulative addition of 993 tonnes of aluminium to Lake Rotorua. Although dosing of the inflow to Lake Rotoehu has been sporadic, a total of 128 tonnes of aluminium have been dosed to the lake since 2011. The University of Waikato was contracted by the Bay of Plenty Regional Council to conduct on-going monitoring of sediment aluminium concentrations in lakes Rotorua and Rotoehu as part of their resource consent conditions for alum dosing to these lakes.

Lake Rotorua

The 2024 sediment survey supports previous finding by Özkundakci et al. (2013) and Tempero and Davies-Calway (2020) of no observable accumulation of alum-derived aluminium in the main basin of Lake Rotorua (sites Ra9–15), with mean sediment total aluminium content ranging between 4–5 g Al kg⁻¹. However, there have been notable changes in sediment aluminium content at the shallow (≤ 5 m) near-shore sites and the deep (45 m) volcanic crater north of Motutara Point (i.e., sites Ra1–Ra8). Surface sediment (0–4 cm depth) mean total aluminium concentrations at sites Ra2 (5.1 g Al kg⁻¹ DW) and Ra3 (6.2 g Al kg⁻¹ DW) east of Sulphur Bay were notably elevated compared to the <3 g Al kg⁻¹ DW observed at the same sites in 2019 and 2020. In comparison, there were reductions of 2–4 g Al kg⁻¹ DW surface sediment total aluminium at sites Ra6 and Ra7 between 2020 and 2024, as well as corresponding reductions in the proportion of amorphous aluminium at sites Ra6 and Ra7 in the surface and middle (6–14 cm depth) sections of the sediment profiles.

The apparent change in the distribution of near-shore sediment aluminium could be explained by periodic resuspension of alum floc during extreme wind events such as tropical storms (Evans 1994; Gibbs et al. 2016). Shallow lakes are particularly prone to sediment resuspension as wind-induced wave action propagates through the water column and can exceed the critical shear stress threshold of the bottom sediment (Zhang and Chen 2023). In Lake Rotorua, Burger (2006) reported that sediment resuspension was estimated to contribute up to 71 % of total particulate matter occurring at a site located at 7 m depth. To the east and west of the Motutara Point volcanic crater, Lake Rotorua is comparatively shallow with water depths of 5–10 m and with a wind fetch of up to 8 km during prevailing westerly winds (Figure 2). Sediment in this zone is primarily composed of sand–gravel down to a depth of ~ 12 cm where it transitions to silt-mud, indicating that this is a relatively high energy zone that regularly exceeds the critical shear stress threshold for fine sediments. Hydrodynamic modelling of winter storm events in Lake Rotorua showed that wind speeds >7 m s⁻¹ for 16 hours can induce near bottom current velocities of up to 20 cm s⁻¹ at a depth of 20 m (Gibbs et al 2016). Consequently, sediment resuspension may affect nearly all of the

Rotorua lakebed during winter storms. Such hydrodynamic conditions often result in particle sorting, either by resuspension of particles sitting on the surface of the lakebed or infiltration of the gravels by fine particles such as alum floc (Cui et al. 2008). Infiltration of recently formed alum floc may have occurred at site Ra1, resulting in the observed peak in amorphous aluminium below 12 cm sediment depth (Figure 6). However, there was no corresponding increase in total aluminium, suggesting that the majority of alum-derived aluminium in this area of the lake may have been resuspended.

Previous sediment surveys conducted in 2019 and 2020 at sites Ra6 and Ra7 in Te Ruapeka Bay, have notable peaks in alum-derived aluminium in the surface sediments, signifying alum floc discharged from the Utuhina Stream was likely accumulating in this area (Tempero 2019; Tempero and Davies-Calway 2021). Te Ruapeka Bay is comparatively sheltered from prevailing westerly winds and extensive beds of *Lagarosiphon major* may also provide a dampening effect against wave disturbance at low to moderate wind velocities (i.e., $<7 \text{ m s}^{-1}$) (Madsen et al. 2001; Gibbs et al. 2016). However, given that amorphous aluminium concentrations were only elevated in the surface sediment it is probable that periodic resuspension of alum floc likely occurs during large storm events when easterly or northerly gale-force winds prevail. Such storm events likely result in disturbance and resuspension of fine sediment particles in Te Ruapeka Bay. The resuspended particles may then be transported to different areas of the lake or even discharged through the Ōhau Channel. Resuspension and transportation of sediment from Te Ruapeka Bay may help explain the observed decrease in total aluminium at sites Ra6 and Ra7 and the corresponding increase at sites Ra2 and Ra3. The transportation of resuspended material may also extend to the main basin of the lake, although dispersion over such a large area likely results in dilution to the point where alum-derived aluminium cannot be distinguished from natural background levels in the sediment.

Changes in sediment aluminium content were also observed at sites in (Ra5) and (Ra8) which were associated with the deep volcanic crater north of Motutara Point. At 45 m (Ra5) and 21 m (Ra8) depth, both sites are likely to be too deep to experience wind-driven sediment resuspension, and it is reasonable to expect that these areas would accumulate alum floc given their proximity to the discharge points of the Utuhina Stream and Sulphur Bay, as well as resuspended material from other near-shore areas. This is supported by the fact that Ra5 and Ra8 had the greatest mean sediment aluminium content in the 2020 sediment survey (Figure 4). However, marked decreases in both total and amorphous aluminium were observed in the 2024 survey (Figures 4, 7 and 8), suggesting this area may experience disturbance of sedimented material, resulting in dispersal and irregular distribution of alum floc. Visible geothermal activity is present at Sulphur Bay and the boundary of the Rotorua geothermal field is thought to extend north from Rotorua City into Lake Rotorua (Allis and Lumb 1992). Recent high-resolution hydrographic surveys have confirmed the presence of several active hydrothermal vents in the area associated with the deep volcanic crater (de

Ronde et al. 2023), this geothermal activity provides a possible mechanism for localised sediment disturbance, preventing sedimentation or redispersing alum floc and resulting in large variations in observed sediment aluminium content between survey periods.

Total aluminium concentrations in the main basin of Lake Rotorua (i.e., site Ra9–15) have remained consistent across survey periods, with mean total aluminium content of approximately 5 g Al kg⁻¹ DW. Although, the percentage of amorphous aluminium was ~10–15% lower at sites Ra11–12 compared to previous surveys (Figure 9). It is uncertain if this reduction reflects natural processes such as mineralisation or simply measurement variability. Regardless, these findings indicate that the mass of alum-dosed aluminium capable of adsorbing sediment released DRP cannot be distinguished from natural background levels at these sites.

Lake Rotoehu

Alum dosing of the inflow to Lake Rotoehu was halted from 18 July 2018 to 9 December 2020 following a determination that insufficient alum was reaching the main basin of the lake at a level that would have an effective impact on lake DRP concentrations. Dosing was restarted in December 2020 at a reduced rate sufficient to remove DRP from the Waitangi Stream. After 9 months the dosing station was again shut down for maintenance and had not been restarted by January 2024 due to increased lake water levels flooding the dosing station in 2023. The limited alum dosing between the 2020 and 2024 sediment survey resulted in the addition of 3.6 tonnes of aluminium or 13.3 kg Al day⁻¹, compared to peak dose rates of 59.8 kg Al day⁻¹.

The major reduction in Lake Rotoehu alum dosing is reflected in the proportion of amorphous aluminium in the sediment profiles. At sites located close to the discharge point of the Waitangi stream (i.e., Rh1–3, Figure 3) the proportion of amorphous aluminium in the surface sediments declined from ~80–100% in 2016 to <20% in 2024. This likely reflects the natural processes as amorphous aluminium hydroxide floc ages to form the inert mineral gibbsite (Cooke et al. 2005; Berkowitz et al. 2006). While legacy accumulation of total aluminium can still be observed in the Te Wairoa Bay sites this is unlikely to result in ecological impacts due to its inert nature and, over time, will become buried as fresh sediment is deposited. This process can be observed at site Rh2 (Figure 11), where the peak in total aluminium has moved lower in the sediment profile from 2016 to 2024. Given these results, further sediment surveys of Lake Rotoehu would not be beneficial unless alum dosing was resumed.

Future investigations

Some uncertainty remains as to the fate of alum-derived aluminium in Lake Rotorua. The observed variation in sediment aluminium indicates that sedimented alum floc in the near-shore area of Lake Rotorua is being resuspended and transported during extreme storm

events. However, there appears to be little evidence to support significant deposition of alum-derived aluminium in the main basin of the lake. This may be due to mineralisation of the floc, making it analytically indistinguishable from natural catchment-sourced aluminium, or possible discharge of particles from the lake via the Ōhau Channel. Hydrodynamic modelling, incorporating particle tracking, may assist in determining the fate of alum floc discharged from the Utuhina and Puarenga Streams. Storm event simulations may also provide insights into the threshold for sediment resuspension and transportation of particles under extreme conditions. This will provide an improved understanding of the effectiveness of alum dosing to Lake Rotorua and can be strengthened by coupling with a mass balance budget of alum-derived aluminium dosed to Lake Rotorua.

Conclusions

Sediment cores were taken from Lake Rotorua and Lake Rotoehu in January 2024 covering both near-shore and main basin sites. Total and amorphous aluminium content was assessed to determine where alum derived aluminium was accumulating in Lake Rotorua.

The main conclusions were:

1. The distribution of sediment aluminium has changed in the near-shore zone of Lake Rotorua with sites to the west of Motutara Point declining in total aluminium while sites to the east have notably increased.
2. Geothermal activity in the deep crater north of Motutara Point may be disturbing and resuspending sedimented alum floc.
3. Aluminium levels have remained relatively consistent in the main basin of Lake Rotoehu.
4. Comparatively little alum has been dosed to Lake Rotoehu since the 2020 and the proportion of amorphous aluminium in the sediment has significantly declined indicating natural mineralisation is occurring.

Recommendations

1. On-going sediment monitoring for alum-derived aluminium should incorporate quantification of both total and amorphous aluminium.
2. Unless alum dosing is resumed, further sediment aluminium surveys of Lake Rotoehu are not essential.
3. Consideration should be given to hydrological modelling of alum floc with incorporation of storm event scenarios. When coupled with a mass balance budget of alum-derived aluminium, this will provide an improved understanding of the fate of aluminium in Lake Rotorua.

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Appendices

Appendix 1. Locations and water depth of sediment coring sites in Lake Rotorua, January 2024.

2020 & 2024 Core sites	Previous Site designation		2024 Sampling date	Latitude	Longitude	Water depth (m)
	Tempero and Hamilton (2016)	Tempero (2019)				
Ra1		Site 1	22 January 2024	-38.094591	176.314635	4.8
Ra2		Site 2	22 January 2024	-38.111994	176.296850	4.9
Ra3		Site 3	22 January 2024	-38.124765	176.279512	4.7
Ra4		Site 4	22 January 2024	-38.127519	176.268509	22.1
Ra5	RU2	Site 5	22 January 2024	-38.122032	176.265637	45.1
Ra6		Site 6	22 January 2024	-38.113216	176.249619	4.9
Ra7		Site 7	22 January 2024	-38.121759	176.253555	4.8
Ra8	RU3		22 January 2024	-38.119067	176.266617	21.2
Ra 9	RU4		23 January 2024	-38.109183	176.268767	17.4
Ra10	RU5		23 January 2024	-38.093233	176.272283	20.2
Ra11	RU7		23 January 2024	-38.085100	176.263533	20.4
Ra12	RU9		23 January 2024	-38.073183	176.270417	22.0
Ra13	RU11		23 January 2024	-38.063167	176.289367	19.8
Ra14	RU13		23 January 2024	-38.044100	176.306700	16.4
Ra15	RU15		23 January 2024	-38.071233	176.310417	12.3

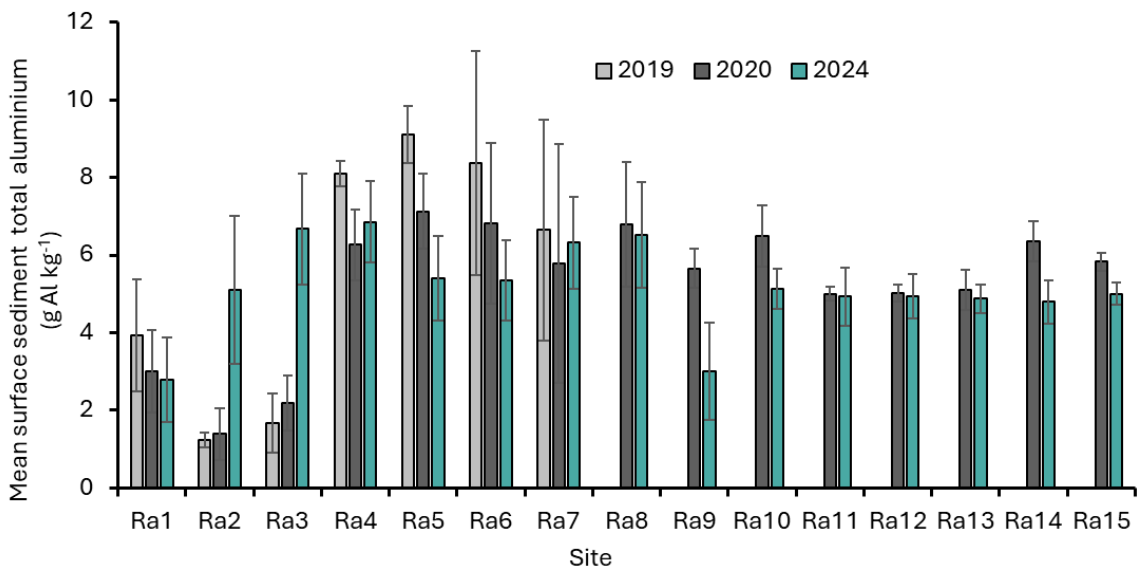
Appendix 2. Locations of sediment coring sites in Lake Rotoehu 2016, 2020 and 2024.

Site	latitude	longitude	2024 Water depth (m)
Rh 1	-38.0333	176.54633	2.2
Rh 2	-38.0324	176.54545	2.6
Rh 3	-38.0301	176.54230	4.2
Rh 4	-38.0271	176.53566	9.5
Rh 5	-38.0237	176.53097	11.2
Rh 6	-38.0190	176.52973	12.0
Rh 7	-38.0146	176.52998	12.0

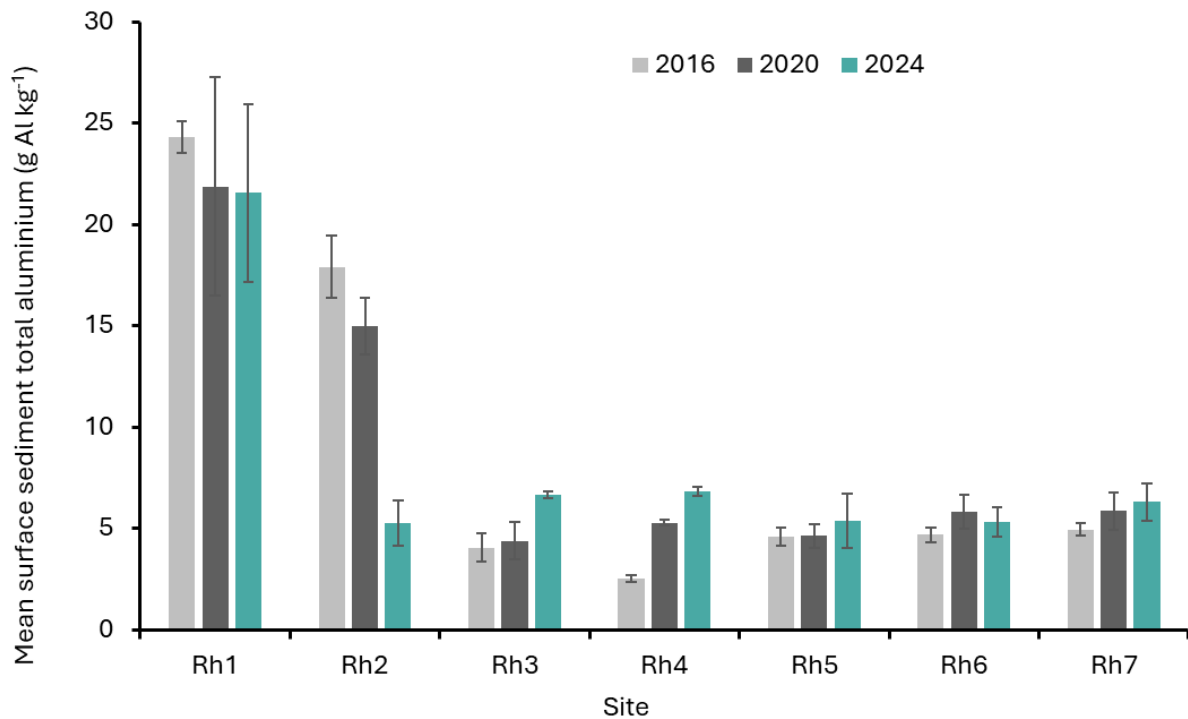
Appendix 3. Intact sediment core with suspected alum floc at the sediment surface.



Appendix 4. Comparative changes in surface sediment (0–4 cm depth) mean aluminium concentrations from 2019–2024 in Lake Rotorua (± 1 standard deviation).



Appendix 5. Comparative changes in surface sediment (0–4 cm depth) mean aluminium concentrations from 2016–2024 in Lake Rotoehu (± 1 standard deviation).



Appendix 6. Comparative geographic distribution of mean surface (1–4 cm depth) sediment total aluminium content observed in surveys of Lake Rotoehu in December 2020 (left) and the January 2024 (right).

