

# Aluminium Content in Near-Shore Sediments of Lake Rotorua

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## ERI Report Number 132

Client report prepared for Bay of Plenty Regional Council  
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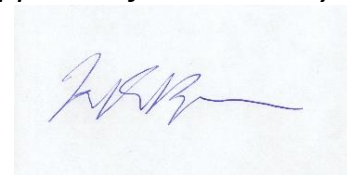
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# Executive Summary

The application of alum (aluminium sulphate) is widely used for lake restoration. Aluminium binds dissolved reactive phosphate (DRP), reducing its availability to phytoplankton and inhibiting algal blooms. The Bay of Plenty Regional Council has conducted continuous alum dosing of the Utuhina Stream since 2006 and the Puarenga Stream from 2010 to 2018. This has resulted in the addition of more than 730 tonnes of aluminium to Lake Rotorua. Improvements in Lake Rotorua water quality occurred concurrently with peak alum dosing, although sediment surveys conducted in 2012 and 2015 were unable to locate significant depositional areas of aluminium floc in the main basin of Lake Rotorua.

Elevated amorphous aluminium (i.e., recently deposited aluminium) was reported at sites closest to the Utuhina and Puarenga discharge points in the 2015 sediment survey, indicating that aluminium was potentially accumulating in the nearshore zone. The University of Waikato was contracted by the Bay of Plenty Regional Council to conduct a follow-up survey of near-shore sites along the southern edge of Lake Rotorua. In addition to sediment total and amorphous aluminium content, total phosphorus content was also determined. Amorphous aluminium is recognised as the fraction of total aluminium able to adsorb dissolved phosphorus, sequestering it from the water column. For this study it was assumed that increased proportions of amorphous aluminium were primarily derived from alum dosing.

Seven sediment cores were taken from Lake Rotorua from April to May 2019. Coring sites were chosen to represent three potential near-shore depositional zones. Sites 1–3 covered the area from Sulphur Bay north-east to Te Pohue Bay, Sites 4 and 5 sampled sediment from within the 45 m deep volcanic crater north of Sulphur Point, and Sites 6 and 7 were selected to assess the accumulation of aluminium discharged from the Utuhina Stream into the area west of Sulphur Bay between Motutara Point and Kawaha Point. Analysis of the sediment cores from Sites 1–3 showed little or no accumulation of aluminium. The sediment in this area was primarily comprised of gravel and coarse sand indicating a high energy environment structured by wind-driven wave action. Aluminium floc entering this area from Sulphur Bay is likely resuspended and transported to other areas of the lake or discharged from the lake via the Ohau Channel. Cores from Sites 4 and 5 taken from the 45 m deep crater off Motutara Point had significantly elevated levels of both total and amorphous aluminium extending beyond 20 cm sediment depth. Located between the discharge points of the Utuhina and Puarenga Streams, this area likely receives sedimented aluminium from both stream alum dosing and geothermally derived aluminium from Sulphur bay. The depth of amorphous aluminium indicates a local sediment accumulation rate greater than the mean rate for Lake Rotorua of 0.3–1 cm per year. This may be due to the proximity of the discharge points of the Utuhina and Puarenga Streams and the greater depth preventing sedimented material from being resuspended by wave action. Sites 6 and 7 also showed accumulation of total and

amorphous aluminium, although this was notably restricted to surface sediments (0–4 cm depth). Extensive beds of *Lagarosiphon major* were present in this area likely trapping alum floc and preventing the type of wave-driven resuspension occurring at Sites 1–3. However, the sediment composition at these sites was primarily coarse sand rather than the fine silt observed at greater depths (i.e. deeper than 10 m), this may indicate that periodic resuspension of material is occurring during storm events.

These findings suggest that alum-derived aluminium is primarily accumulating in the nearshore area close to the discharge points of the Utuhina and Puarenga Streams between Kawaha Point and Motutara Point, with significant accumulation also occurring in the volcanic crater north of Motutara Point. The lack of aluminium accumulation in the main lake basin indicates that secondary sediment capping effects are unlikely to be substantial, and recent improvements in the water quality of Lake Rotorua may be driven by other factors, such as a positive feed-back loop between reductions in organic matter sedimentation and nutrient regeneration.

It is recommended that future sediment monitoring surveys of Lake Rotorua include the nearshore zone between Kawaha Point and the crater area off Motutara Point, and that analysis should include quantification of sediment amorphous aluminium content. Hydrodynamic 3-D modelling of contaminant tracers may provide further insights into the proportion of alum-derived aluminium discharged from the lake compared to that which is permanently mineralised in the lake sediment.

# Acknowledgements

I would like to thank Troy Baisden and John Tyrrell for reviewing this document. Joe Butterworth and Chris Eager provided technical field support and ICP-MS analysis was conducted by Amanda French. This project was also financially supported through the Enhancing the Health and Resilience of New Zealand Lakes (Contract UOWX1503) and funding for the Bay of Plenty Regional Council Chair in Lake Restoration.

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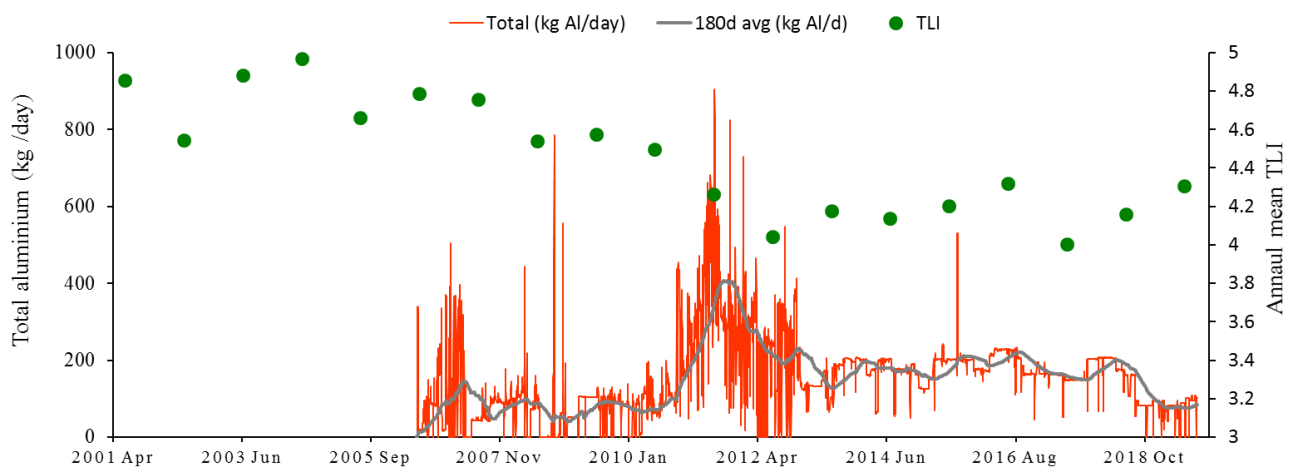
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# Introduction

Continuous alum (aluminium sulphate) 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. Alum dosing is intended to sequester dissolved phosphorus, removing it from the water column, thereby reducing primary production and improving water clarity. A calculated rolling average showed that the combined average aluminium dose for the Utuhina and Puarenga Streams was c. 202 kg Al day<sup>-1</sup> with peaks of up to c. 800 kg Al day<sup>-1</sup> for the period July 2010 – June 2014 (Hamilton et al. 2015), this is correlated with decreases in lake trophic lake index (TLI) (Figure 1). Alum dosing to the Puarenga Stream was halted on 30 August 2018 and is currently under review. As of 15 May 2019 a total of 730.5 tonnes of aluminium have been dosed to Lake Rotorua.



**Figure 1. Daily aluminium dose rate to Lake Rotorua from 2006 to 2019 and mean annual trophic lake index (TLI) from 2001 to 2019.**

When added to water alum forms aluminium hydroxide ( $\text{Al}(\text{OH})_3$ ) which adsorbs dissolved phosphorus and coagulates suspended solids (Cooke et al. 2005). The resulting aluminium flocs may either be lost from the system through outflows or settle to the bottom sediment. In shallow lakes or lake margins, wind-driven resuspension may cause settled flocs to be transported to deeper parts of the lake (Cooke et al. 2005). Bioturbation, gas ebullition and advection, as well as storm surges, can disturb or bury surface sediment and thus, move the aluminium flocs into deeper sediment layers, potentially rendering it ineffective for controlling bioavailable phosphorus in the lake (Egemoose et al. 2013, Özkundakci et al. 2013). Once settled, flocculated  $\text{Al}(\text{OH})_3$  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). However, during the early part of this process, before crystallisation,  $\text{Al}(\text{OH})_3$  is still able to bind bioavailable phosphorus, providing the additional



benefit of attenuating sediment phosphorus release under hypoxic conditions (Welch and Cooke 1999).

Previous bottom-sediment surveys of Lake Rotorua were conducted prior to (Pearson 2007), and following (Özkundakci et al. 2013; Tempero and Hamilton 2016) initiation of alum dosing of inflows to Lake Rotorua. Post-alum dosing surveys have primarily focused on the main basin of Lake Rotorua with sediment coring sites all located in water depths >10 m (Tempero and Hamilton 2016) (Figure 2). Sediment surveys conducted by Özkundakci et al. (2013) and Tempero and Hamilton (2016) did not detect significant increases in surface (0–4 cm) sediment total aluminium concentrations compared to pre-alum dosing. However, Tempero and Hamilton (2016) reported increases in the proportion of surface sediment amorphous aluminium in relation to total aluminium at the core sites closest to the Utuhina and Puarenga inflows. This was consistent with deposition of aluminium floc from alum dosing and supported by the observation that sediment pore water dissolved phosphorus concentrations were reduced at four sites located near to the discharges of the Utuhina and Puarenga Streams (Tempero and Hamilton 2016). It was concluded that alum derived aluminium from was not accumulating in the main basin of Lake Rotorua as assumed, but was either being deposited in the nearshore zone (<10 m depth) or remained in suspension and discharged from the lake (Tempero and Hamilton 2016).

The University of Waikato was contracted by the Bay of Plenty Regional Council to conduct an additional sediment survey of the nearshore zone of Lake Rotorua from Kawaha Point to Motutara Point and north to Te Pohue Bay, including the 45 m deep crater off Motutara Point (Figure 3). Sediment cores were taken from seven sites and analysed for total and non-crystalline aluminium content in order to determine if alum derived aluminium was accumulating in the nearshore environment of Lake Rotorua. Recommendations for future monitoring will also be provided.

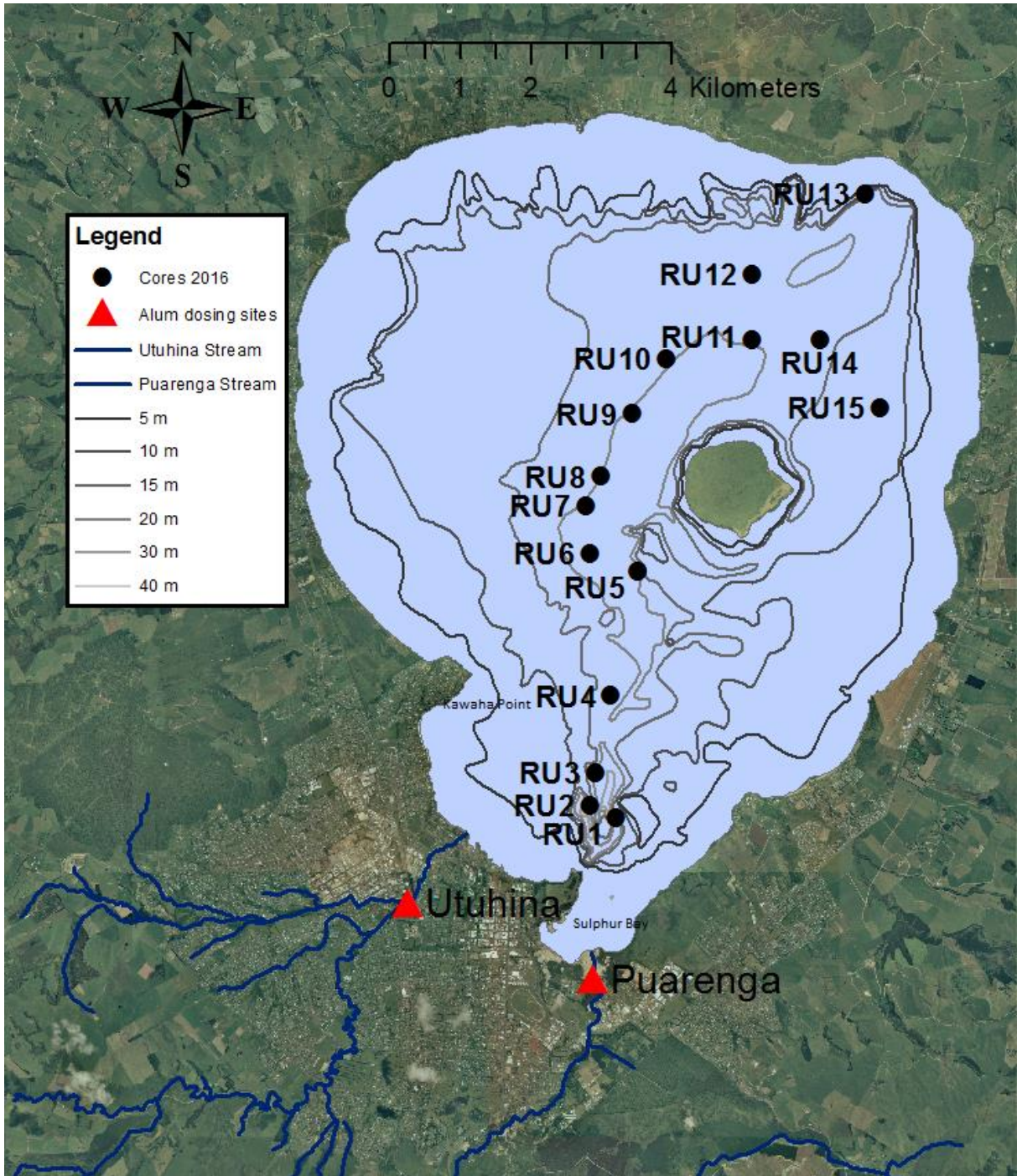


Figure 2. Locations of sediment cores taken in 2012 by Özkundakci et al. (2013) and 2015 by Tempero and Hamilton (2016). Utuhina and Puarenga sub-catchments with alum dosing sites are also shown. Reproduced from Tempero and Hamilton (2016).

# Methods

## Study Site

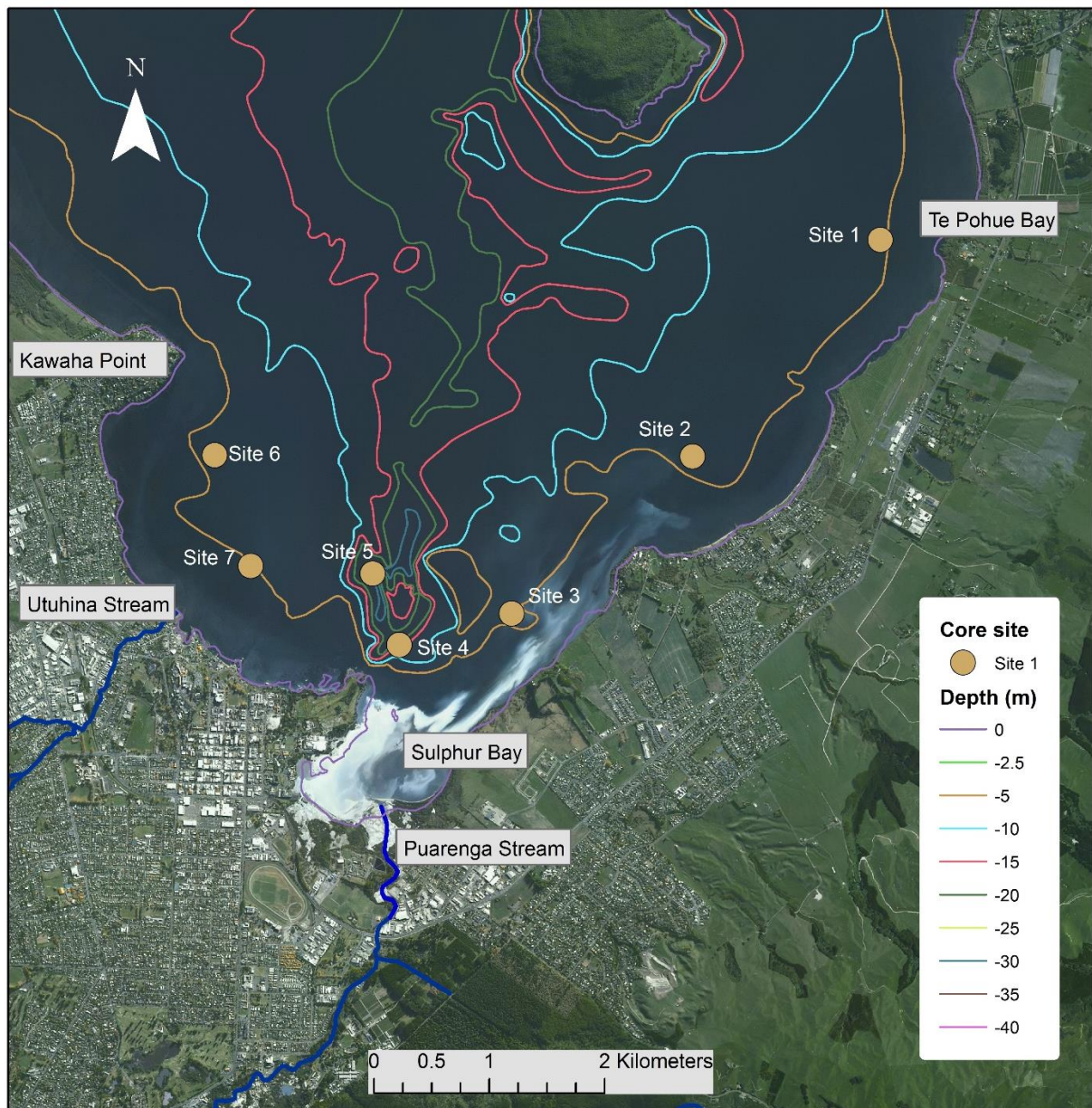
Lake Rotorua is the largest of 12 lakes jointly managed under the Rotorua Te Arawa Lakes Programme. It has a surface area of 80.6 km<sup>2</sup>, a mean depth of 10.8 m (maximum depth 45 m), a total water volume of 0.85 km<sup>3</sup> and polymictic stratification patterns (Burger et al. 2011). Lake 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 2010 (Donald et al. 2018) (Appendix 1).

## Sediment survey

Seven sediment cores were collected over two days from near-shore locations along the southern edge of Lake Rotorua (Figure 3), coring site coordinates, sampling dates and site depths are presented in Appendix 2. Coring Sites 1, 2, 3, 6 and 7 were selected based on geographic location to stream inflow sites and the criteria of being on or near the 5 m isobath. The 5 m water depth was selected as it was assumed this depth would be sufficiently deep to avoid wave resuspension of sediment and allow sufficient fine sediment deposition for intact core retrieval using a Swedish gravity corer while being within sufficient proximity to alum discharge points. However, the sediment composition at coring Sites 1, 2, 3, 6 and 7 consisted of coarse gravel and sand at Sites 1, 2 and 3 and dense beds of *Lagarosiphon major* at Sites 6 and 7 precluding the retrieval of intact cores. A modified technique was employed, whereby the corer barrel was pushed into the sediment and then retrieved by a scuba diver. Sites 4 and 5 were selected to test the hypothesis that alum floc was accumulating in the deep crater north of Motutara Point, these two sites were able to be surveyed without the assistance of a scuba diver as the sediment composition of fine particles was similar to that observed in other sediment cores from depths >10 m.

Following Özkundakci et al. (2013) and Tempero and Hamilton (2016) 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 along with c. 10 cm of the overlying water. Once the core was retrieved water samples were taken from the overlying water for determination of total nutrients (nitrogen and phosphorus) and dissolved nutrients (dissolved reactive phosphate, ammonium, and nitrate). A custom-made, gas-tight sampling chamber, designed to minimise exposure of potentially anoxic sediment to the air, was then fitted to the core barrel and the core was extruded by a piston from the base of the core. Excess supernatant water overflowed the top of the core 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 sediment depth the sediment was added to tubes at 2-cm intervals. Small amounts of residual

overflowing sediment were discarded. Sediment samples were stored on ice until analysis in the laboratory.



**Figure 3. Lake Rotorua nearshore sediment coring sites with Utuhina and Puarenga Streams.**

In addition to sediment coring, water column profiles were taken at each coring site using a conductivity-temperature-depth (CTD) profiler (SBE 19 plus SEACAT Profiler, Seabird Electronics Inc.), with additional mounted sensors for dissolved oxygen (DO) concentration (Seabird Electronics), chlorophyll fluorescence (Chelsea MiniTracka II) and beam transmittance (WetLabs C-star).

## **Sediment and nutrient analysis**

Sediments were centrifuged at 4000 rpm (2900 G) for 15 minutes and the resulting supernatant pore water filtered using acid washed Swinnex filter holders and Whatman GF/C microfiber filters before being analysed for dissolved reactive phosphate concentrations. The centrifuged sediment was then dried at 50°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 conc. HNO<sub>3</sub> and 0.33 mL conc. HCL. Samples were then digested at 80°C for 1 hr in a circulating water bath followed by the addition of 50 mL milli-Q water. Digested samples were centrifuged and 15 mL of the supernatant filtered using 0.2 µm cellulose acetate filters (Satorius, Germany). The sample and control blank digests were then analysed for phosphorus and aluminium using inductively coupled plasma mass spectrometry (ICP-MS model Agilent 8900 with a triple-quadrupole).

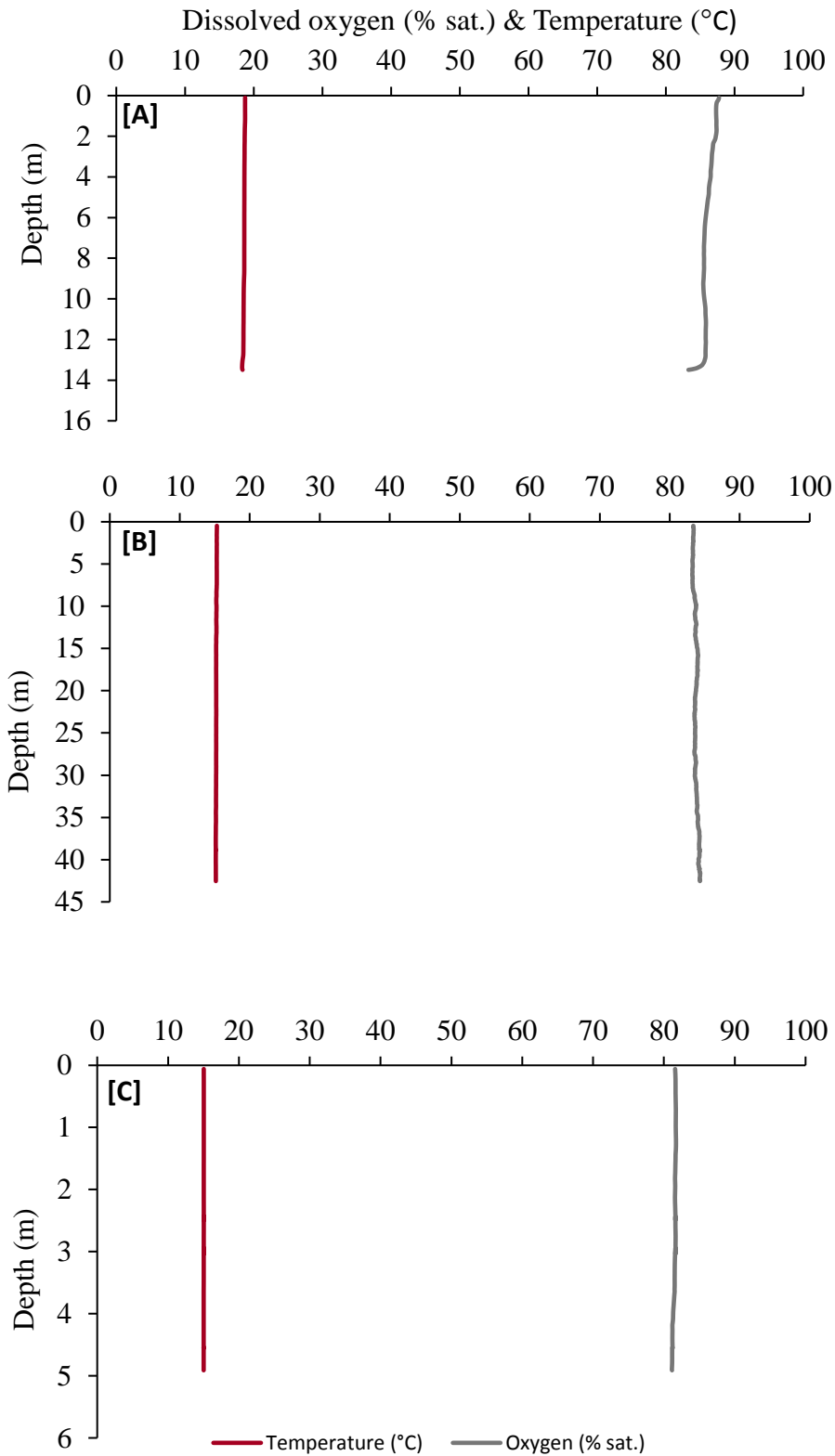
Sediment non-crystalline aluminium content was determined by ammonium oxalate digestion following a modified method of Hodges and Zelazny (1980). Sediment (0.2 g) was shaken with 50 mL 0.2 N ammonium oxalate (Sigma, Australia) (pH 3) for 2 h in the dark, followed by centrifugation for 5 min at 5000 rpm.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

Water nutrient concentrations were analysed using a Flow Injection Analyser 8500 Series II (FIA+ 8000 Series, Zellweger Analytics, Inc. Hach). Phosphate was analysed using LACHAT QuickChem method 31-115-01-1-H; ammonium was analysed using LACHAT QuickChem method 31-107-06-1-B and LACHAT QuickChem Method 31-107-04-1-A was used to analyse nitrate/nitrite. Limits of detection were 0.001 mg N L<sup>-1</sup> for NO<sub>2</sub>, NO<sub>3</sub>, 0.002 mg N L<sup>-1</sup> for NH<sub>4</sub> and 0.001 mg P L<sup>-1</sup> for PO<sub>4</sub>.

# **Results**

## **CTD Profiles**

Conductivity, Temperature, Depth (CTD) profiles were conducted at the same time as cores retrieval. Site 4 was sampled on 11 April 2019 and all other sites on 15 May 2019, temperature and dissolved oxygen profiles for Sites 4 and 5 and a representative profile (Site 2) for the remaining shallow sites are presented in Figure 4. The lake appeared well mixed on both sampling dates with no evidence of hypoxia in the bottom waters.



**Figure 4. Temperature (°C) and dissolved oxygen (% saturation) profiles for Lake Rotorua, (A) Coring Site 4 sampled on 11 April 2019, (B) Coring Site 5 sampled on 15 May 2019 and (C) Coring Site 2 sampled on 15 May 2019 and is representative of the other shallow coring sites sampled on the same date.**

## Sediment Surface Water Nutrient Concentrations

Apart from Site 7, nutrient concentrations measured from the water overlying the seven sediment cores were relatively consistent between sites (Table 1). The elevated total nitrogen and total phosphorus concentrations at Site 7 are likely due to disturbance and resuspension of surface sediments during core retrieval.

**Table 1. Nutrient concentrations from water overlying nearshore sediment cores taken from Lake Rotorua.**

Core site	Total Nitrogen (mg L <sup>-1</sup> )	Total Phosphorus (mg L <sup>-1</sup> )	Total Ammoniacal-N (mg L <sup>-1</sup> )	Nitrite-N (mg L <sup>-1</sup> )	Nitrate-N (mg L <sup>-1</sup> )	Dissolved Reactive Phosphorus (mg L <sup>-1</sup> )
Site 1	0.30	0.038	0.020	< 0.002	0.013	< 0.004
Site 2	0.25	0.024	0.035	< 0.002	0.005	< 0.004
Site 3	0.24	0.026	0.017	< 0.002	0.003	< 0.004
Site 4	0.20	0.022	0.012	< 0.002	0.002	0.008
Site 5	0.18	0.022	< 0.010	< 0.002	< 0.002	< 0.004
Site 6	0.27	0.034	< 0.010	< 0.002	0.009	< 0.004
Site 7	0.81	0.092	0.042	< 0.002	0.017	< 0.004

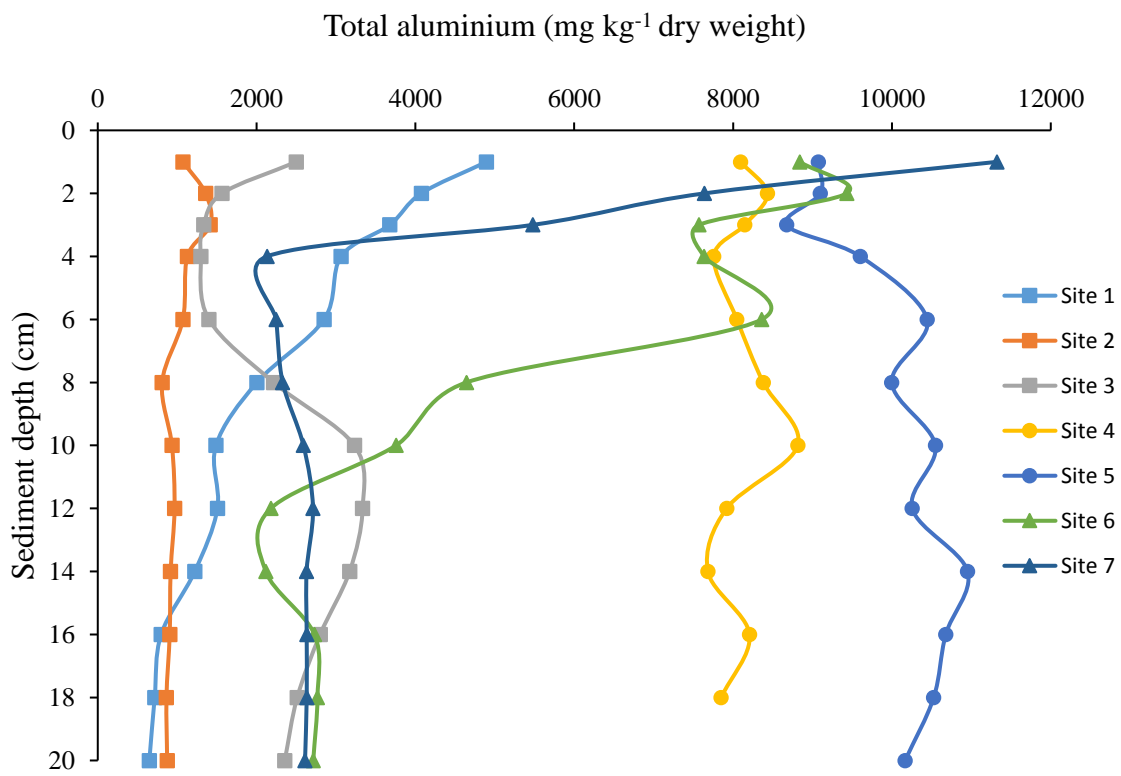
## Core Composition

Visual inspection of the sediment cores showed no evidence of aluminium floc at the sediment-water interface in any of the sediment cores. The cores contained no distinguishing tephra layers that could be used for dating, although a sand layer was evident below the surface gravel of Sites 1–3. Intact sediment cores were difficult to obtain from Sites 1–3 due to the coarse, compacted nature of the sediment. At these sites, the top 6–10 cm of sediment was primarily composed of coarse sand and gravel transitioning to finer sand and silt below 12 cm. Cores from sites 3, 6 and 7 also contained fragments of vegetative material, likely derived from the *Lagarosiphon major* beds in these areas. Cores from the deeper Sites 4 and 5 were composed of silt and clay particles and were free from vegetation.

## Sediment Aluminium Content

Sediment total aluminium content exhibited distinct distribution profiles in relation to geographic location. Cores from the deeper, crater sites (Sites 4 and 5) had higher mean total aluminium content (mean Al Site 4 8,120 mg kg<sup>-1</sup>; mean Al Site 5 10,001 mg kg<sup>-1</sup>) than the mean of the remaining cores (mean Al 2,944 mg kg<sup>-1</sup>) and aluminium content was comparatively elevated throughout the core profiles. Cores from Sites 6 and 7, which were located closest to the Uthina Stream inflow, had notable increases total aluminium content in near surface (0–4 cm depth) in comparison to deeper sediment (12–20 cm) with Site 7 exhibiting a distinct dissociation with the rest of the profile above 4 cm. In contrast to Sites

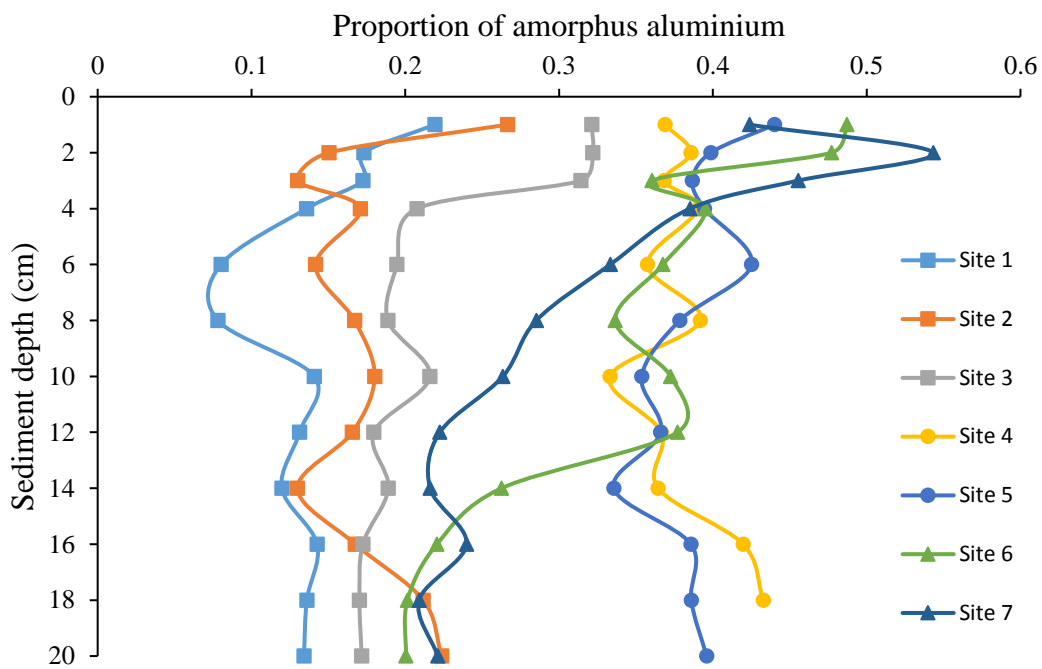
4–7, Sites 1–3, located to the east of Sulphur Bay, showed little evidence of total aluminium accumulation (Figure 5).



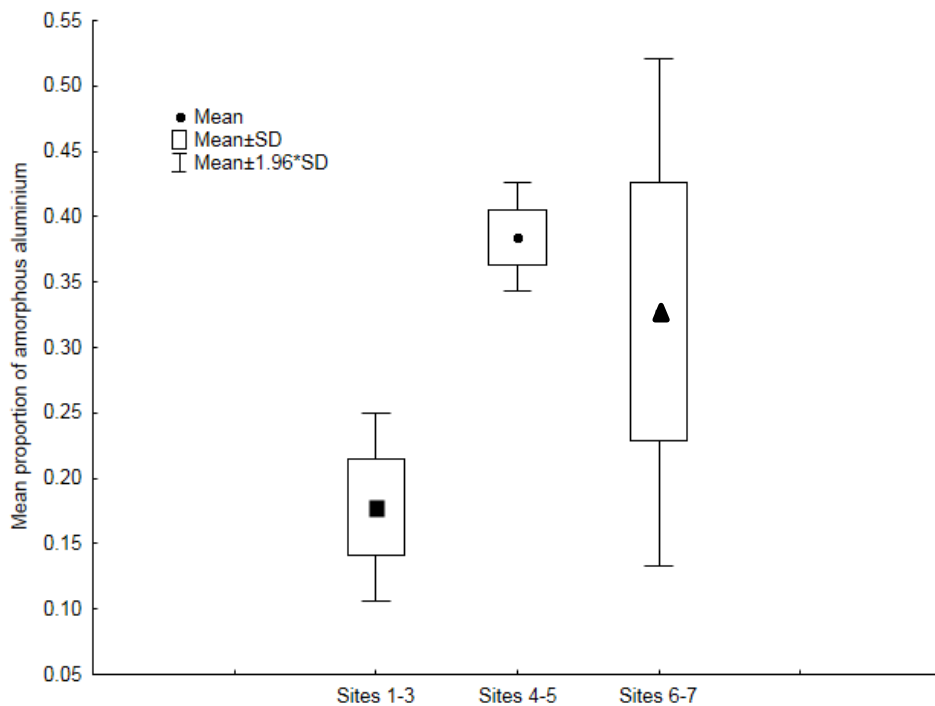
**Figure 5. Vertical profiles of total aluminium content in seven nearshore cores taken from Lake Rotorua.**

Vertical profiles of the proportion of amorphous (non-crystalline) aluminium to total aluminium (Figure 6) exhibited a similar pattern to that observed for total aluminium. Higher proportions of amorphous aluminium were observed in the surface sediments of Sites 4–7 compared to Sites 1–3, although Site 3 did have a notable increase in amorphous aluminium content in the surface sediments compared to deeper (>4 cm depth) sediment. To determine if statistically significant differences in amorphous aluminium content existed between geographic locations within the lake, proportional amorphous aluminium data was grouped by geographic location (Sites 1–3, Sites 4–5 and Sites 6–7) and means of proportion calculated for each depth. A Friedman test performed on the grouped data indicated a significant difference ( $P < 0.001$ ) in the mean proportions of amorphous aluminium (Figure 7), with grouped Sites 1–3 being significantly lower than Sites 4–5.





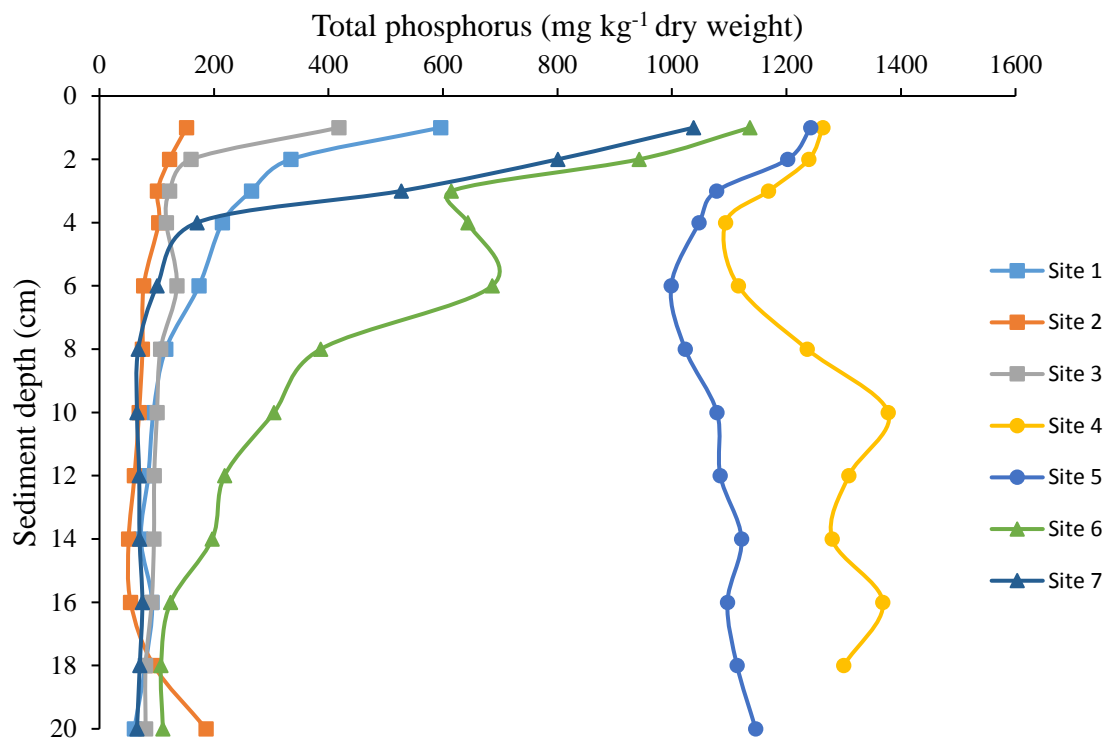
**Figure 6. Vertical profiles of proportional amorphous (non-crystalline) aluminium content in seven nearshore sediment cores from Lake Rotorua.**



**Figure 7. Mean proportional amorphous aluminium content in nearshore sediment cores from Lake Rotorua grouped by geographic location (Sites 1–3, Sites 4–5 and Sites 6–7).**

## Sediment Phosphorus Content

Vertical profiles of sediment core total phosphorus content generally reflected the same distribution patterns as for total aluminium content (Figure 8). Apart from Sites 4 and 5, phosphorus content was elevated in the surface (>4 cm depth) sediments compared to deeper (<12 cm depth) sediments. Notable increases in phosphorus content in the surface sediments over the deeper sediments were also observed for Sites 6 and 7.



**Figure 8. Vertical profiles of total phosphorus content in cores of Lake Rotorua bottom sediment taken from seven nearshore sites.**

Due to the porous nature of the sediment, pore water could not be reliably extracted from the cores and pore water dissolved reactive phosphorus concentrations were unable to be reported.

# Discussion

The Utuhina and Puarenga inflows to Lake Rotorua have been continuously dosed with alum since 2006 and 2010, respectively. This has resulted in the addition of 730.5 tonnes of aluminium to Lake Rotorua. Sediment cores from 15 sites in Lake Rotorua were taken in 2012 and again in 2015 to determine the fate of aluminium entering the lake, but little evidence of aluminium accumulation was found in the sediments from main lake basin (Özkundakci et al. 2013; Tempero and Hamilton 2016). Tempero and Hamilton (2016) did report elevated levels of amorphous (non-crystalline) aluminium in several sites closest to the Utuhina and Puarenga discharge points, indicating deposition of newly derived aluminium. It was hypothesised that alum floc discharged from the Utuhina and Puarenga streams was not dispersing into the main basin as assumed, but was settling in the nearshore area and/or accumulating in the 45 m deep volcanic crater located approximately 850 m north of Motutara Point. The University of Waikato was contracted by the Bay of Plenty Regional Council to conduct a follow up study of the nearshore sediments from Kawaha Point on the western side of the lake along the southern edge of Lake Rotorua to Te Matawera Bay in the east. Coring site locations were selected to be sufficiently close to discharge points of aluminium floc from the Utuhina and Puarenga streams but have sufficient water depth to avoid wave resuspension of sediment. Two cores were also taken from the crater off Motutara Point. Sediment cores were sectioned and independently digested for total aluminium and phosphorus using aqua regia and for amorphous aluminium using ammonium oxalate before target elemental levels were determined by ICP-MS.

Assuming an increased proportion (i.e., >0.35) of amorphous aluminium in lake sediment was due to alum dosing, the distribution of both total and amorphous aluminium in cores from Sites 6 and 7 is consistent with the hypothesis that aluminium from alum dosing is accumulating much closer to the discharge points of the Utuhina and Puarenga Streams than originally assumed. Hydrodynamic modelling of Lake Rotorua by Abell et al. (2015) demonstrated that the discharge point of the Utuhina Stream into Te Ruapeka Bay generally experiences lower wind and water column speeds under prevailing south-west and north-east wind conditions when compared to adjacent areas. This lower energy environment would likely experience less alum floc resuspension compared to areas to the north and east. Sites 6 and 7 were also covered by extensive beds of *Lagarosiphon major* which may be inhibiting dispersal and resuspension of alum floc discharged from the Utuhina Stream. This effect has also been observed in Lake Rotoehu where extensive beds of *Ceratophyllum demersum* at the discharge point of the Waitangi Soda Stream has resulted in the accumulation of floc from the dosing station upstream, inhibiting it from dispersing into the main lake basin (Tempero and Hamilton 2016; Eager 2017). However, the sediment composition was primarily sandy beneath the surface layer of fine sediment, coupled with the comparatively shallow depth of increased aluminium accumulation this may indicate that wave action is periodically sufficient to resuspend finer particles.

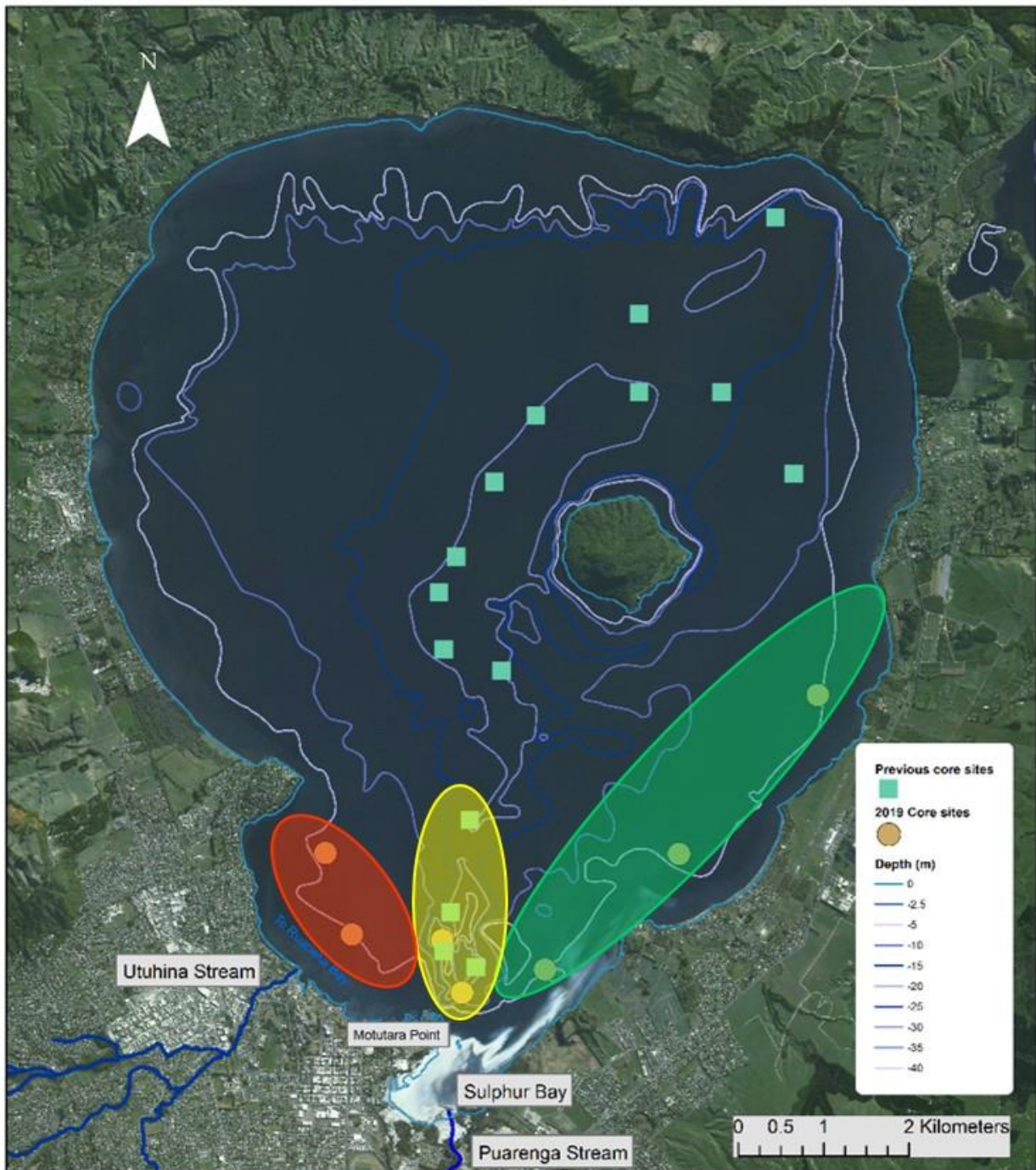
Sites 4 and 5 also displayed increased levels of total and amorphous aluminium, but levels were elevated throughout the core profile rather than just the surface sediment. Visually obvious layers such as the 1886 Tarawera tephra were not captured in the present sediment survey precluding direct calculation of sedimentation rates without substantial additional analyses, such as  $^{210}\text{Pb}$  or  $^{137}\text{Cs}$  or other markers. For Lake Rotorua, Trolle et al. (2008) calculated a net sedimentation rate for the period 1886–2006 of  $0.3 \text{ cm yr}^{-1}$ , and Pearson (2007) estimated a rate of up to  $1.0 \text{ cm yr}^{-1}$ . Employing these sedimentation rates provides an estimated sediment accumulation range of 5–13 cm for the period 2006–2019, but elevated levels of aluminium extend beyond the expected sediment accumulation range for alum dosing. This result may be explained through a number of mechanisms; firstly, accumulation of aluminium floc appears to be highly spatially variable and not a reliable indicator of the mean sedimentation rate. The proximity of Sites 4 and 5 to catchment discharge points (including storm water discharge from Rotorua City) may combine with the negative buoyancy of suspended sediments, including alum floc, to cause greater sediment accumulation rates in the vicinity of the 45 meter-deep crater compared to those derived for the main basin of Lake Rotorua by Trolle et al. (2008) and Pearson (2007). In addition, hydrodynamic model simulations of suspended particles discharged from Sulphur Bay also support the greater accumulation rate of sediment in this area of the lake due to convergence of gyre currents and lower prevailing wind velocities (Abell et al. 2015). The greater than expected extent of amorphous aluminium at Sites 4 and 5 may also be due accumulation of naturally occurring aluminium discharged from Sulphur Bay, an area known to have water concentrations of up to  $1 \text{ mg Al L}^{-1}$  (c.f.  $0.02 \text{ mg Al L}^{-1}$  in the main lake) from geothermally derived aluminium (Landman and Ling 2009). When this natural aluminium source is considered in conjunction with alum derived aluminium discharged from the Puarenga and Utuhina Streams it is not unexpected that total and amorphous aluminium levels are elevated to a significant depth at Sites 4 and 5.

In comparison to Sites 4–7, increased sediment aluminium content was not detected at Sites 1–3. This was unexpected as it has been noted that the predominantly westerly wind in the Rotorua area tends to direct a plume of water and associated suspended material, including alum floc, from Sulphur Bay north-east along the shoreline (Hamilton and Tempero 2016; Ling 2017). Hydrodynamic modelling has also shown that under south west wind conditions suspended particles discharge from Sulphur Bay are driven north-east along the near-shore to towards the Ohau Channel. Surface sediments in this area were composed of gravel and coarse sand, suggesting the area experiences high energy disturbance from waves, driven by the predominantly westerly and northerly winds and aided by the large fetch distance to this area of the lake. In contrast with the sites 6 and 7, it is likely the low benthic macrophyte abundance and significant wave action in this area of the lake facilitates the resuspension of finer sediment particles, resulting in transport out of Lake Rotorua through the Ohau Channel.

From the current sediment survey and previous surveys of Lake Rotorua by Özkundakci et al. (2013) and Tempero and Hamilton (2016) it appears that the main depositional areas for alum derived aluminium in Lake Rotorua are Te Ruapeka Bay, the discharge point for the Utuhina Stream and the crater north of Motutara Point. The fate of aluminium discharged from Sulphur Bay is likely dependent on the prevailing wind direction, either sedimenting to the deeper crater area under southerly or easterly wind conditions or kept in suspension under westerly wind conditions and potentially discharged from the lake. A graphical summary of these conclusions is presented in Figure 9.

Lake Rotorua was not stratified at the time of sediment coring, and there was no evidence of either dissolved reactive phosphorus (DRP) or ammonium release from lake sediments into the hypolimnion. The failure to collect sediment pore water for DRP analysis precluded a comparative assessment of phosphorus retention by amorphous aluminium in the lake sediments. However, it has been previously noted by Özkundakci et al. (2013) and Tempero and Hamilton (2016) that it was highly unlikely that a sediment capping effect from alum dosing of the Puarenga and Utuhina streams was occurring and improvements in the water quality of Lake Rotorua during the years immediately following the initiation of alum dosing were not wholly due to in-lake phosphorus sequestration. This is supported by the current study which indicates that aluminium capable of sequestering phosphorus is primarily accumulating in a highly spatially limited area of the lake, with only a comparatively small area of accumulation occurring within the hypolimnetic hypoxic zone during periods of stratification (i.e., Figure 9 yellow area).

Future sediment surveys focusing on aluminium accumulation from alum dosing should focus on the nearshore areas between Kawaha Point and the crater area off Motutara Point as this appears to be the area of accumulation from the Utuhina Stream. A proportion of aluminium floc discharged from Sulphur Bay appears to be unaccounted for, as no significant aluminium accumulation was observed in the south-east nearshore zone of the lake despite the discharge plume from Sulphur Bay regularly covering this area. Wave resuspension and water currents may be dispersing floc making it difficult to discern from background aluminium levels. Alternatively, wave driven resuspension may keep the floc in suspension resulting in it being discharged through the Ohau Channel. Analysis of aluminium content in sediment cores taken from the Ohau discharge point to Lake Rotoiti may provide some insight as to the extent of aluminium discharged from Lake Rotorua. Additional insight might result from consideration of processes including flocculation, resuspension and negative buoyancy in combination with hydrodynamic modelling targeted to discharge from the Utuhina and Puarenga Streams.



**Figure 9. Differing depositional zones of alum derived aluminium. The red zone indicates the likely area of aluminium deposition from the Utuhina Stream. The yellow zone indicates the deeper volcanic crater area where aluminium discharged from both the Utuhina Stream and Sulphur Bay is likely accumulating. The green zone represents a relatively broad shallow region where alum floc primarily discharged from Sulphur Bay is prevented from permanently settling due to wind-driven wave resuspension.**

# Conclusions

Seven sediment cores were taken from nearshore sites along the southern edge of Lake Rotorua in 2019. Total and amorphous aluminium content and total phosphorus content was assessed to determine where alum derived aluminium was accumulating in Lake Rotorua.

The main conclusions were:

1. Sediment aluminium content was elevated in the nearshore area between Kawaha Point and the crater area off Motutara Point. This is likely due to alum treatment of the Utuhina and Puarenga inflows, although geothermally sourced aluminium from Sulphur Bay may be a contributing factor.
2. Aluminium does not appear to be accumulating in the south-eastern nearshore zone east of Sulphur Bay. This is likely due to wind driven resuspension of fine sediment resulting in dispersal of floc to other areas of the lake or discharge from the lake through the Ohau Channel.
3. The finding of recent aluminium accumulation in the nearshore zone confirms the hypothesis that aluminium from alum dosing is not accumulating in the main basin of the lake and is unlikely to provide a “sediment cap” capable of adsorbing phosphorus released from these areas during hypoxic conditions.

## Recommendations

1. Future sediment monitoring surveys for alum derived aluminium should focus on the nearshore zone between Kawaha Point and the crater area off Motutara Point.
2. Monitoring of sediment aluminium accumulation should also include assessment of amorphous aluminium content to distinguish alum-derived aluminium from natural background crystalline aluminium.
3. Given the apparent dichotomy between water quality improvement and the limited distribution of aluminium floc in the hypolimnetic zone an improved understanding of the relationship between phosphorus sequestration from alum dosing and water quality improvements is required to ensure optimal lake management is achieved.
4. Further insights into the fate of alum-derived aluminium discharged from the Utuhina and Puarenga streams may be achieved through 3-D hydrodynamic modelling of contaminant tracers.

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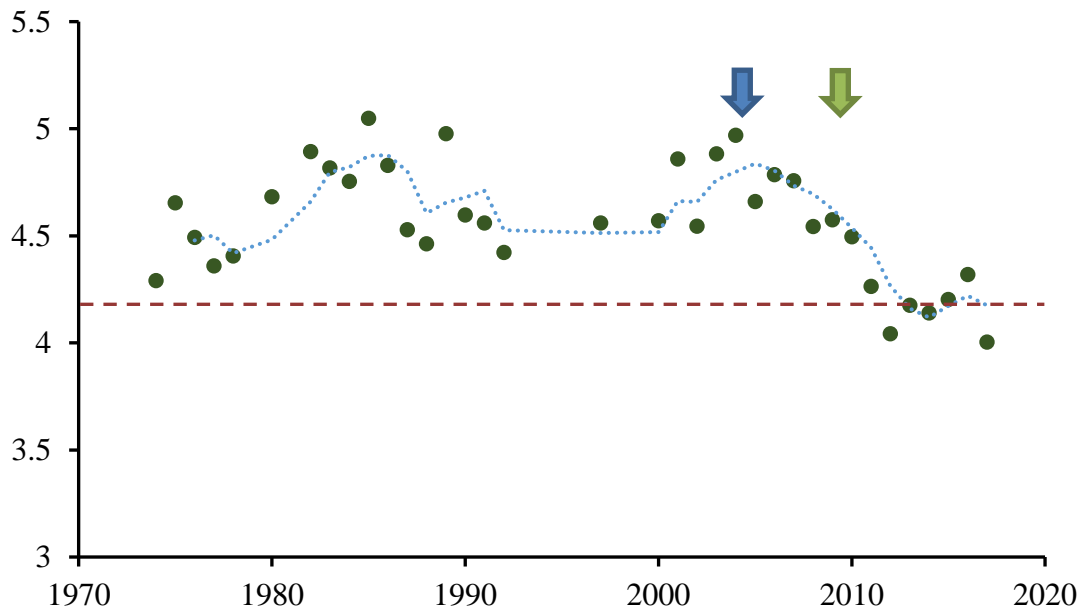
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# Appendices

## Appendix 1. Annual mean Trophic Lake Index (TLI) values for Lake Rotorua



Annual mean TLI values for Lake Rotorua from 1974 to 2017. Blue dotted line indicates 3-year running average. Blue and green arrows indicate initiation of alum dosing to the Utuhina and Puarenga Streams, respectively. Red dashed line indicates target TLI value of 4.2 for Lake Rotorua.

## Appendix 2. Locations and water depth of sediment coring sites in Lake Rotorua.

Lake Rotorua nearshore coring locations and water depth.

Core site	Sampling date	Latitude	Longitude	Water depth (m)
Site 1	15 May 2019	-38.094591	176.314635	4.8
Site 2	15 May 2019	-38.111994	176.296850	4.9
Site 3	15 May 2019	-38.124765	176.279512	4.7
Site 4	11 April 2019	-38.127519	176.268509	22.1
Site 5	15 May 2019	-38.122032	176.265637	45.1
Site 6	15 May 2019	-38.113216	176.249619	4.9
Site 7	15 May 2019	-38.121759	176.253555	4.8