

Puarenga Stream Alum Dosing: Effects on Lake Rotorua Biota 2023



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By Grant Tempero and Nicholas Ling
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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: Southerly view into Sulphur Bay from Lake Rotorua.

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Reviewed by:



Matthew Prentice
University of Waikato

Approved for release by:



Charles Lee
Director, Environmental Research Institute

Executive Summary

Following eutrophication in the second-half of the 20th century, Lake Rotorua currently experiences regular algal blooms reducing the recreational amenity of the lake. In 2007, an Action Plan was formulated to limit nutrient inputs to the lake, thereby improving water quality. One approach to reducing dissolved reactive phosphorus reaching the lake was the initiation of continuous alum dosing of the Puarenga Stream in 2010. The aluminium component of alum (aluminium sulphate) binds with dissolved phosphate making it unavailable for uptake by algae and limiting their growth. As a condition of the current resource consent RM18-0213-AP to alum dose the Puarenga Stream, monitoring surveys of lake water, common bully, plant material and macroinvertebrates must be conducted every 5 years to test for bioaccumulation of aluminium.

The University of Waikato sampled the lake water, *Eleocharis acuta* roots, common bully (*Gobiomorphus cotidianus*), kākahi (*Echyridella menziesii*) and chironomid larvae (*Chironomus zealandicus*) at four sites in and around Sulphur Bay in September 2023. Tissue samples were dried, weighed and then digested using tetramethylammonium hydroxide and hydrogen peroxide, followed by solubilisation of metals by acidification. Samples were then diluted, filtered and analysed for aluminium content by Inductively-Coupled Plasma Mass Spectrometry (ICPMS).

Dissolved aluminium concentrations in water samples at all four monitoring sites were lower than the site long-term means of the data from previous monitoring surveys (2012–2020). Aluminium concentrations measured in chironomid larvae were significantly lower at Site 1 compared to the long-term site mean. Further, aluminium concentrations were significantly elevated in kākahi digestive glands at Site 2 and Site 3 compared to long-term site means. Most notably, common bully whole-body aluminium concentrations were significantly elevated at Site 4, which had previously been designated as the reference (unimpacted) site.

Aluminium concentrations in the tissues of biota sampled from within and around Sulphur Bay are likely influenced by dissolved aluminium from geothermal activity. While dissolved aluminium water column concentrations generally decline with distance from Sulphur Bay, biota tissue concentrations appear to be more variable and likely related to periodic inundation by the geothermal plume exiting Sulphur Bay. Mobile species such as common bully are likely to avoid the associated lower pH conditions and move out of the area of influence, while more sedentary species such as kākahi and *Eleocharis* may become locally excluded if the geothermal plume persists. Additional one-off sampling of common bully in Te Ruapeka Bay (i.e., Site 4) is recommended to determine if the elevated concentrations were a singular occurrence due to the intermittent combined influence of aluminium associated with alum dosing of the Utuhina Stream and westward flow of currents exiting Sulphur Bay.

Recommendations

1. Additional one-off sampling of common bully should be conducted in Te Ruapeka Bay to determine whether the elevated tissue aluminium concentrations observed at Site 4 were anomalous or persist at this site.
2. An additional reference site located outside of Te Ruapeka Bay should be included in future Puarenga monitoring surveys.

Table of Contents

Executive Summary	3
Recommendations	4
Table of Contents	5
Introduction	7
Methods	9
Survey sites.....	9
Biota sampling	10
Tissue analysis	10
Statistical analysis.....	10
Results	11
Water column aluminium	11
Biota tissue aluminium.....	11
Discussion.....	15
Conclusions	18
Recommendations	18
Acknowledgements	19
References	19

LIST OF FIGURES

Figure 1. Quantity of aluminium discharged daily (A) and annually (B) to the Puarenga Stream since the commencement of dosing in January 2010. * alum dosing was paused from September 2018 to November 2020 due to system maintenance and COVID-19 restrictions.	8
Figure 2. Monitoring site locations in and around Sulphur Bay. Site 4 was selected as a reference site.	9
Figure 3. Aluminium concentrations ($\mu\text{g L}^{-1}$) from water samples ($n=2$) taken within and around Sulphur Bay September 2023, with comparisons to previous surveys. See Figure 2 for site locations (geometric means $\pm$ geometric standard deviation).	11
Figure 4. Whole body tissue aluminium concentrations in chironomid larvae (mg kg^{-1} dry weight) from sites within and around Sulphur Bay including pre alum dosing, means from survey years 2012–2020 and the current survey conducted in 2023 (geometric means $\pm$ 95% confidence interval). ** indicates a significant difference at $p < 0.01$	12
Figure 5. Aluminium concentrations in the digestive gland of kākahi (mg kg^{-1} dry weight) from sites within and around Sulphur Bay (geometric means $\pm$ 95% confidence interval), ** indicates a significant difference at $p < 0.01$	13
Figure 6. Whole body tissue aluminium concentrations in common bully (mg kg^{-1} dry weight) from sites within and around Sulphur Bay (geometric means $\pm$ 95% confidence interval), ** indicates a significant difference at $p < 0.01$. ND = no data.	14
Figure 7. Aluminium concentrations in the roots of the sedge <i>Eleocharis acuta</i> (mg kg^{-1} dry weight) from sites within and around Sulphur Bay (geometric means $\pm$ 95% confidence interval). ND = no data.	14
Figure 8. Variability in the geothermal plume of water leaving Sulphur Bay. Upper image January 2017, lower image December 2012, Google Earth.	16
Figure 9. Modelled entrainment of Sulphur Bay water along the eastern shoreline in south-westerly winds (after Abell & Hamilton 2015).	17

Introduction

The Lakes Rotorua and Rotoiti Action Plan proposed to lower the Trophic Level Index (TLI) of Lake Rotorua from 4.9 to 4.2 by reducing internal and catchment-derived nitrogen and phosphorus through a number of management actions (EBoP 2009). The plan established sustainable annual external loading targets of 435 tonnes of nitrogen and 37 tonnes of phosphorus to Lake Rotorua. Continuous alum (aluminium sulphate) dosing of the Utuhina and Puarenga streams was proposed as a method to reduce external phosphorus loading by 6 tonnes of dissolved reactive phosphorus (DRP) per year (EBoP 2009). Continuous alum dosing of the Puarenga Stream began in 2010 with annual surveys of biota tissue aluminium concentrations undertaken. In 2021, resource consent for alum dosing was renewed until mid-2031 with the requirement of 5-yearly monitoring surveys. Alum dosing of the Puarenga Stream has been variable, with no alum dosed between September 2018 to November 2020 due to plant maintenance and COVID-19 restrictions (Figure 1A). Total application of aluminium to the Puarenga Stream from January 2010 to 31 December 2023 was 547.9 tonnes, at a mean (excluding 2019) dose rate of 42.1 tonnes of aluminium per year (Figure 1B). The TLI of Lake Rotorua has improved since the initiation of alum dosing, with the annual TLI consistently near the 4.2 target since 2011 (Tempero and Ling 2026).

Alum (aluminium sulphate) sequesters dissolved phosphate making it unavailable for uptake by algae cells. By limiting phosphate availability, algal growth is reduced and algal blooms may be prevented. Once added to water, alum hydrolyses to form aluminium hydroxide, a relatively benign white precipitate with peak abundance occurring at pH 6.3 (Cooke et al. 2005). However, above pH 8.5 and below pH 5.5, more soluble toxic aluminium species predominate. For example, under alkaline conditions (>pH 8.5) toxic $\text{Al}(\text{OH})_4^-$ forms, while below pH 4.5 free monomeric aluminium (Al^{3+}) becomes prevalent. Dissolved aluminium species may cause disruption of osmoregulation and respiration processes in aquatic animals and disrupt phosphorus availability in vascular plants, although toxic thresholds are dependent on species, aluminium concentrations and pH (Gensemer and Playle 1999; Tempero 2015). The hydrolysis reaction of alum also releases hydrogen ions, lowering pH and potentially causing the formation of toxic aluminium species if the receiving environment has a low buffering capacity (Gensemer and Playle 1999; Cooke et al. 2005; Tempero 2015). Landman and Ling (2009) measured bioaccumulated aluminium in a variety of Lake Rotorua biota to provide baseline data on natural aluminium bioavailability prior to the commencement of alum dosing. Subsequent post-dosing monitoring surveys of the Sulphur Bay receiving environment have been conducted on four occasions between 2012–2020 with no detectable effects on biota from alum dosing (Ling 2014; Ling 2016; Ling 2017; Ling 2023).

This report details the survey of biota and water samples collected from around the Sulphur Bay area in September 2023. It reports on biota tissue aluminium concentrations and compares concentrations to those measured in biota from previous surveys. Finally, it

provides an assessment of potential impacts from the addition of bioavailable aluminium to the Puarenga Stream / Sulphur Bay receiving environment.

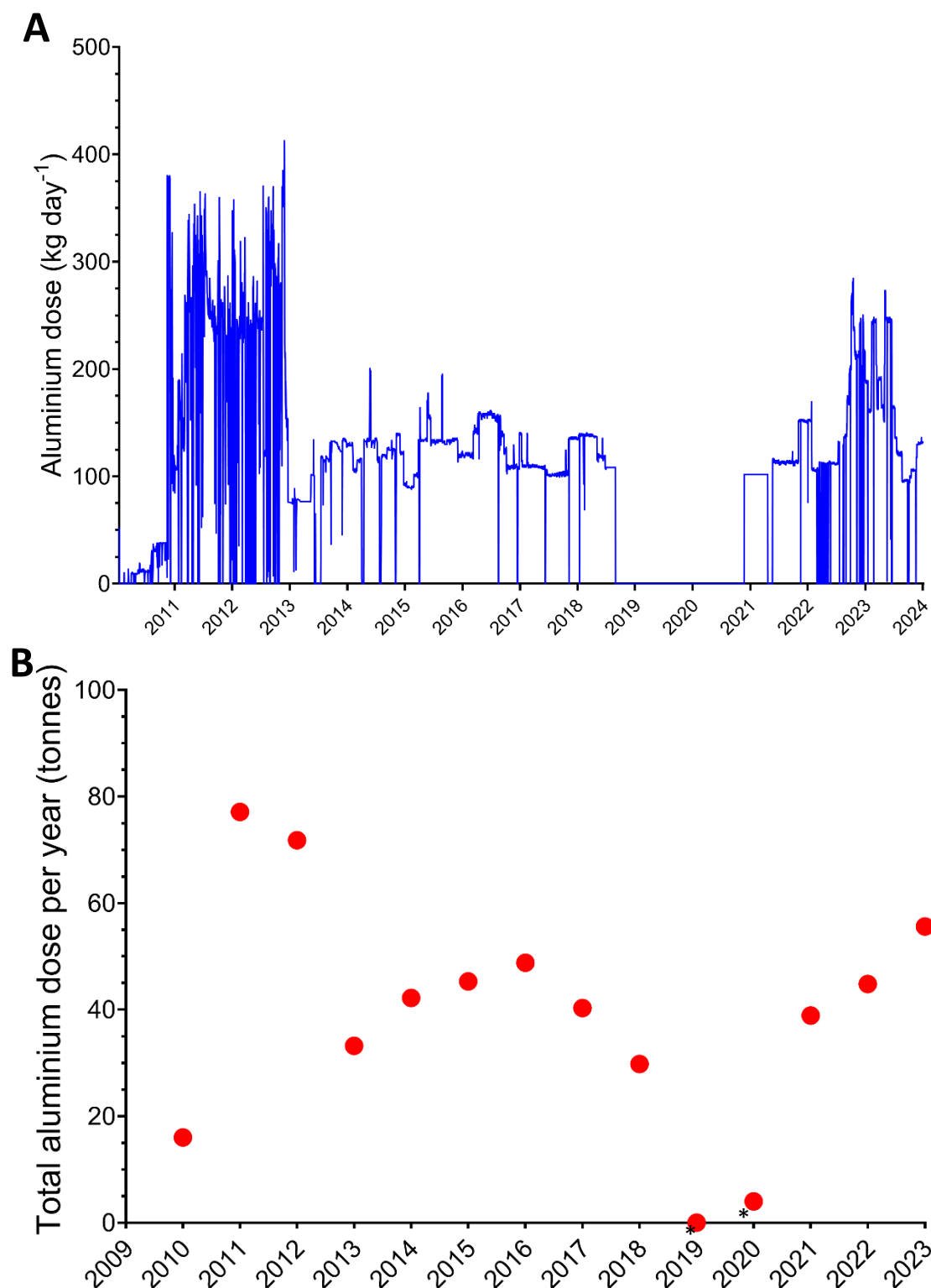


Figure 1. Quantity of aluminium discharged daily (A) and annually (B) to the Puarenga Stream since the commencement of dosing in January 2010. * alum dosing was paused from September 2018 to November 2020 due to system maintenance and COVID-19 restrictions.

Methods

Survey sites

The Puarenga Stream discharges into Sulphur Bay, a continuously active geothermal area, and a designated wildlife reserve on the southern shore of Lake Rotorua. Prior to the commencement of alum dosing a baseline monitoring survey of Sulphur Bay biota was conducted by Landman and Ling (2009). A wide variety of macrobiota was surveyed to determine both the availability of indicator species and the inherent variability in aluminium across organisms and tissue types. Based on those findings, a sampling programme was developed for a suite of indicative organisms and tissue types. Four monitoring sites were selected, three within Sulphur Bay and its receiving environment in Lake Rotorua (Sites 1–3) and an additional site located outside the bay (Site 4) for reference purposes (see Figure 2).

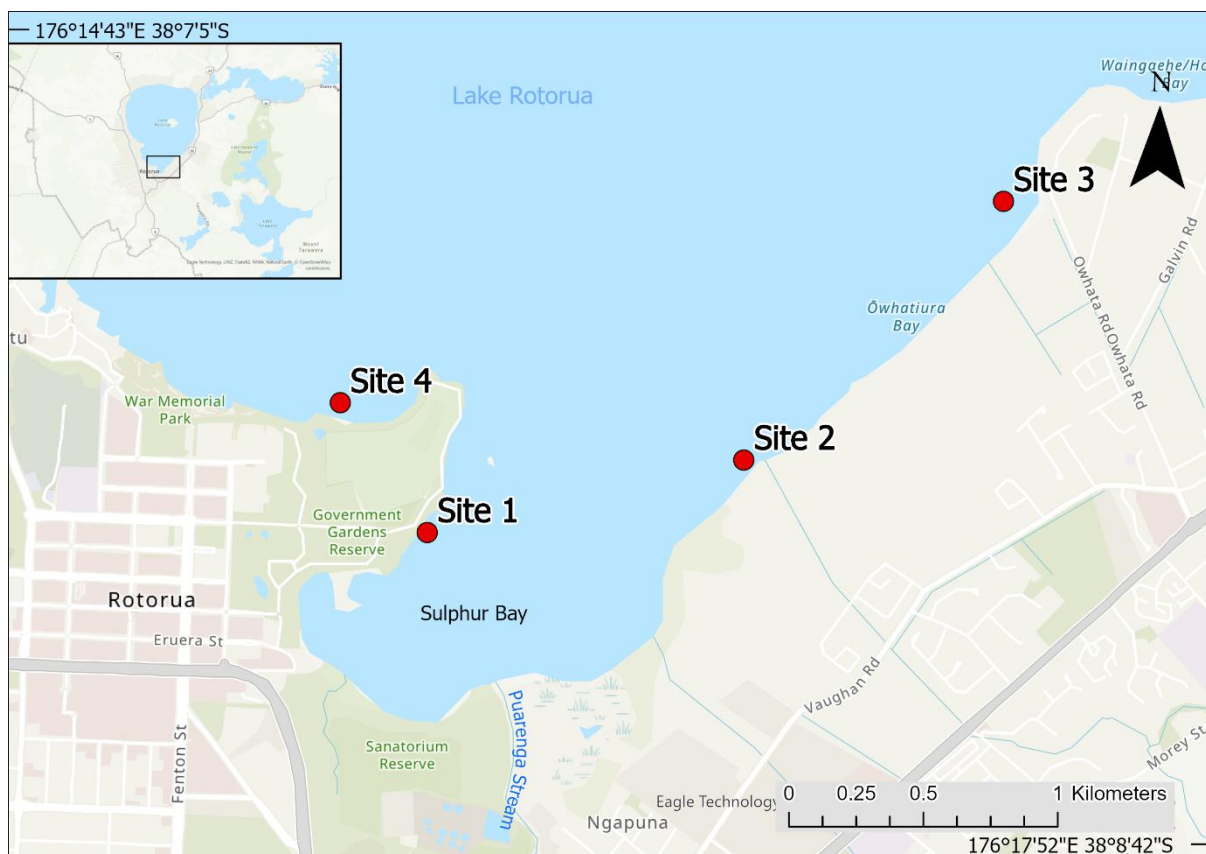


Figure 2. Monitoring site locations in and around Sulphur Bay. Site 4 was selected as a reference site.

Water and biota samples were obtained over two consecutive days in September 2023 following the methods detailed by Landman and Ling (2009). Duplicate 50 mL water samples were collected at each site from just below the water surface. The samples were filtered (0.45 μ m), then acidified with 2% nitric acid prior to Inductively-Coupled Plasma Mass Spectrometry (ICPMS) analysis for dissolved aluminium.

Biota sampling

Chironomid larvae were collected by scooping lakebed sediment into a bucket, followed by manual extraction from the sediment. Common bully (*Gobiomorphus cotidianus*) were collected using set trap lines of 10 Gee minnow traps placed on the lakebed and left overnight. Kākahi (*Echyridella menziesii*) and plant specimens (*Eleocharis acuta*) were collected by scuba diving. Kākahi and common bully were not present at Site 1 and *Eleocharis* was only present at Site 3. A summary of biota samples analysed from each locality is given in Table 1.

Table 1. Summary of plant and animal species availability at each of the selected monitoring sites in and around Sulphur Bay in September 2023. Numbers represent the number of sample replicates analysed by ICPMS. Chironomids = *Chironomus zealandicus* (pooled whole larvae), kākahi = *Echyridella menziesii* (digestive gland only), Common bully = *Gobiomorphus cotidianus* (whole fish), plants = *Eleocharis acuta* (roots only).

	Site 1	Site 2	Site 3	Site 4
Water	× 2	× 2	× 2	× 2
Chironomids	× 5	× 5	× 5	× 5
Kākahi	Not present	× 5	× 5	× 5
Common bully	Not present	× 5	× 5	× 5
Eleocharis	Not present	Not present	× 5	Not present

Tissue analysis

For each site, chironomids were pooled to achieve a sample wet weight of ~0.2 g. Due to the small size of common bully, tissue specific aluminium concentrations could not be determined, therefore whole-body concentrations are reported. For kākahi, digestive glands were removed using acid-washed instruments. *Eleocharis* root samples were carefully removed, then triple-washed with reverse-osmosis water. All tissue samples were dried (60°C for 24 hours), accurately weighed and digested using tetramethylammonium hydroxide, heat and mixing. The colloidal suspension was then partially oxidized by the addition of hydrogen peroxide and metals solubilised by acidification with nitric acid and heating. Samples were then diluted and filtered (0.45 µm) prior to analysis by ICP-MS (School of Science, Waikato University, Hamilton). All tissue element concentrations were determined on a dry weight basis. Method blanks and matrix certified reference material standards (DOLT and DORM; Canadian Research Council) were run in parallel with all samples.

Statistical analysis

Tissue aluminium concentrations were summarised as geometric means with geometric 95% confidence intervals. Statistical tests between groups were conducted on log-normal

transformed data by one-way ANOVA, with selected multiple comparisons. Tests were performed in Prism GraphPad (V. 11.0.2).

Results

Water column aluminium

Water dissolved aluminium concentrations at each site were lower in 2023 compared to the long-term means for each site. Although, the spatial trend of decreasing aluminium concentrations from within Sulphur Bay out into the lake was still evident (Figure 3).

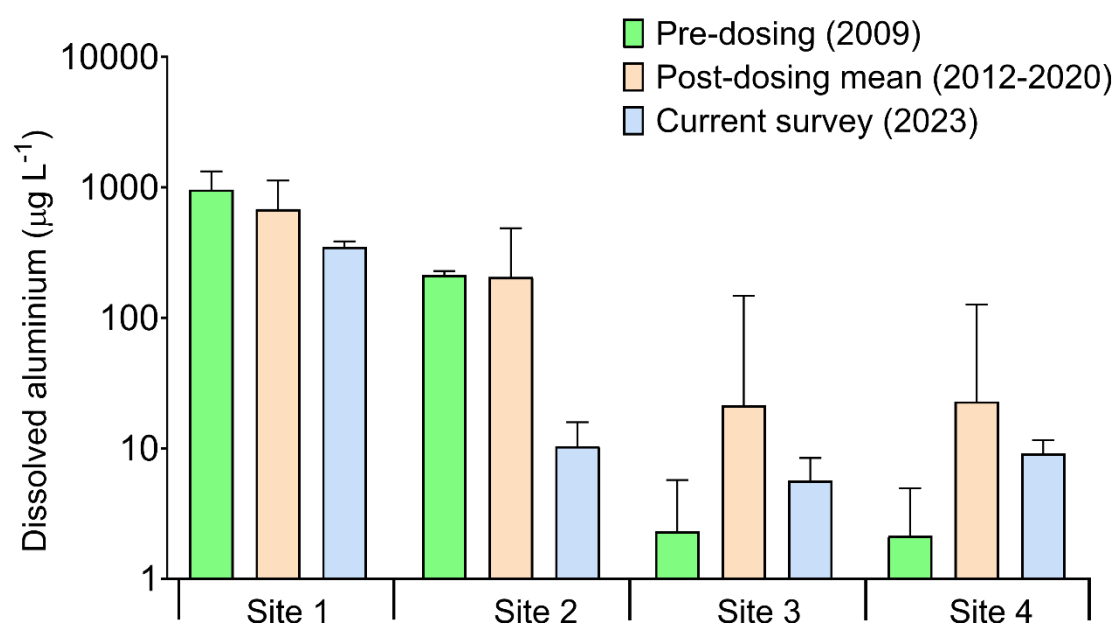


Figure 3. Aluminium concentrations ($\mu\text{g L}^{-1}$) from water samples ($n=2$) taken within and around Sulphur Bay September 2023, with comparisons to previous surveys. See Figure 2 for site locations (geometric means $\pm$ geometric standard deviation).

Biota tissue aluminium

Tissue aluminium concentrations were highest in chironomid larvae, with site mean aluminium concentration ranging from 882–1,529 mg kg^{-1} DW in the 2023 survey compared to post-dosing means 1,933–3,334 mg kg^{-1} DW. However, the only significant difference (lognormal ANOVA, $p < 0.01$) was at Site 1, where 2023 tissue concentrations were lower (932 mg kg^{-1} DW) than the long-term (2012–2020) post-dosing mean concentration (2,717 mg kg^{-1} DW) (Figure 4).

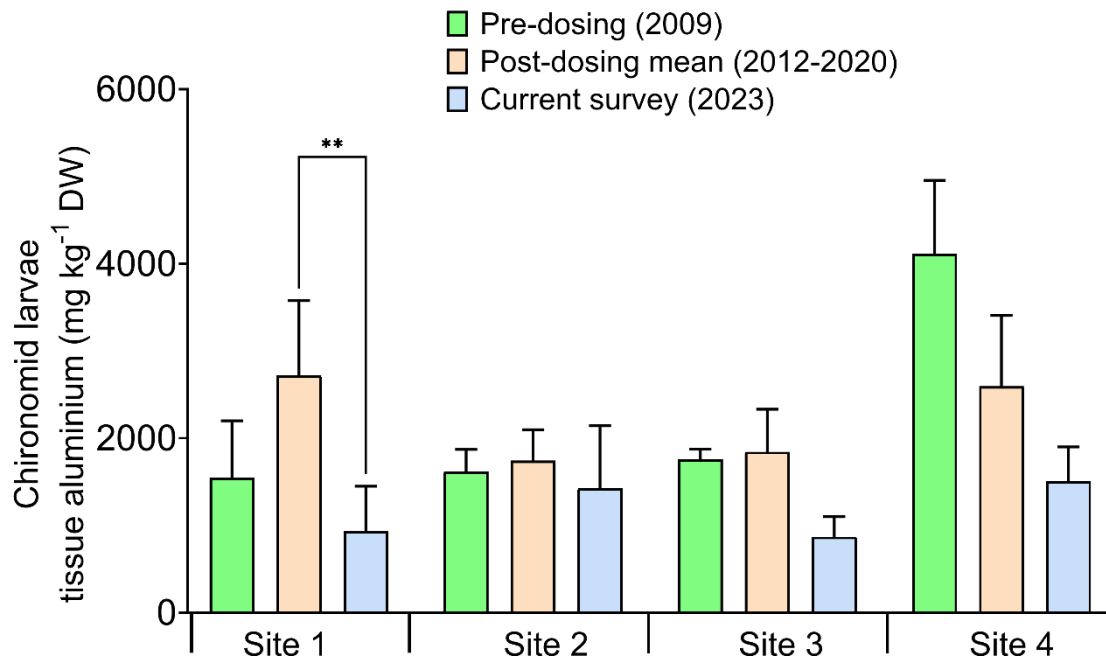


Figure 4. Whole body tissue aluminium concentrations in chironomid larvae (mg kg⁻¹ dry weight) from sites within and around Sulphur Bay including pre alum dosing, means from survey years 2012–2020 and the current survey conducted in 2023 (geometric means $\pm$ 95% confidence interval). ** indicates a significant difference at $p < 0.01$.

Previous post-dosing monitoring surveys reported kākahi digestive gland aluminium concentrations similar to pre-dosing concentrations, with site means ranging between 150–369 mg kg⁻¹ DW (Figure 5). However, digestive gland concentrations from the 2023 survey (range 335–471 mg kg⁻¹ DW) were significantly greater in animals sampled from Site 2 (lognormal ANOVA, $p = 0.002$) and Site 3 (lognormal ANOVA, $p = 0.001$), compared to the post-dosing means for each site. There was no significant difference (lognormal ANOVA, $p = 0.27$) between 2023 samples and post-dosing mean concentrations at Site 4 (Figure 5).

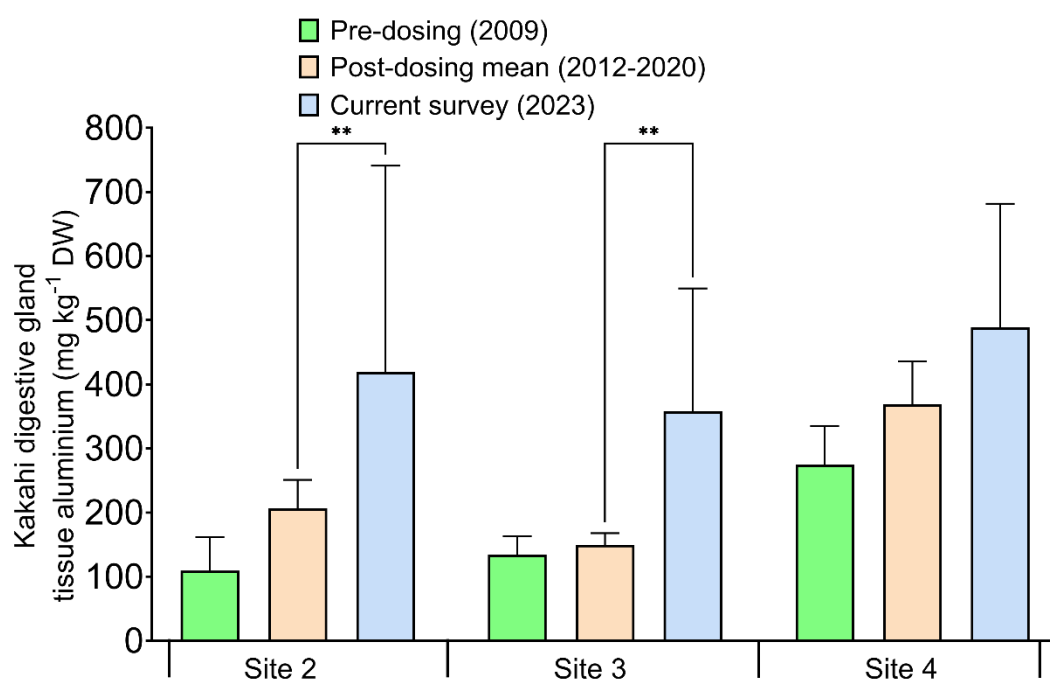


Figure 5. Aluminium concentrations in the digestive gland of kākahi (mg kg⁻¹ dry weight) from sites within and around Sulphur Bay (geometric means $\pm$ 95% confidence interval), ** indicates a significant difference at $p < 0.01$.

The mean whole body tissue aluminium concentration for common bully at Site 4 was significantly (lognormal ANOVA, $p < 0.01$) greater in the 2023 survey (110 mg kg⁻¹) compared to the mean of post-dosing concentrations (17.9 mg kg⁻¹) (Figure 6). However, there were no significant differences between the 2023 survey, and the long-term post-dosing means for Sites 2 and 3.

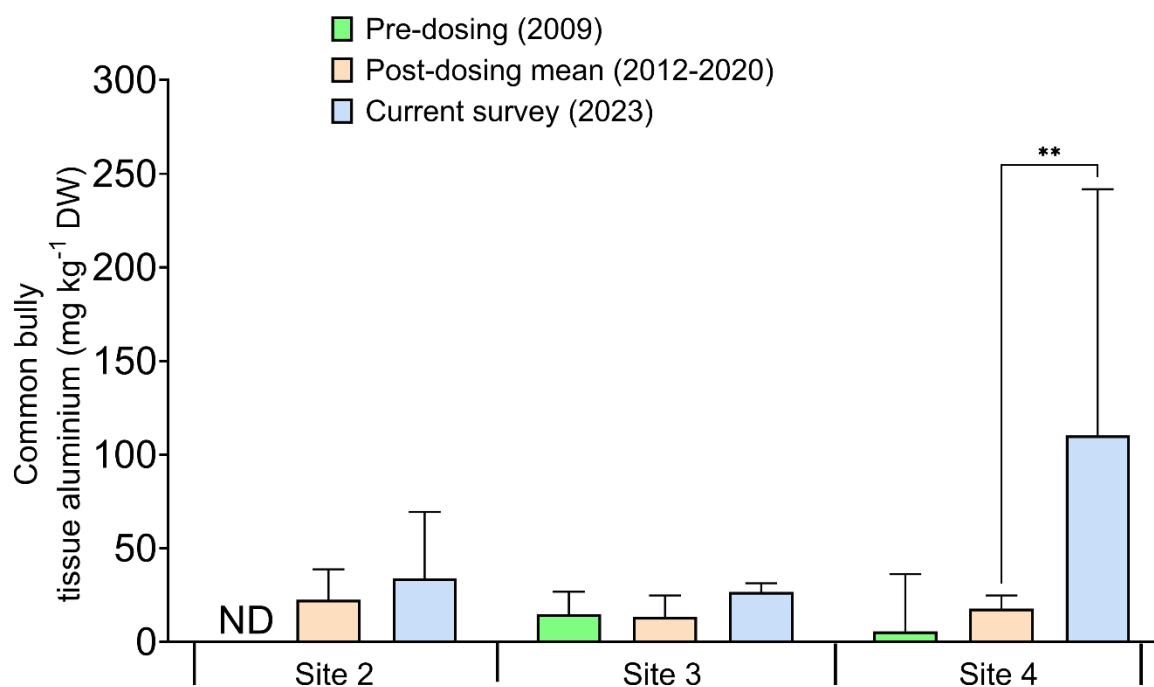


Figure 6. Whole body tissue aluminium concentrations in common bully (mg kg^{-1} dry weight) from sites within and around Sulphur Bay (geometric means $\pm$ 95% confidence interval), ** indicates a significant difference at $p < 0.01$. ND = no data.

Eleocharis was only present at Site 3 in 2023, with root aluminium concentrations similar ($1,433 \text{ mg kg}^{-1}$) to the long-term post-dosing mean ($1,889 \text{ mg kg}^{-1}$) for the site (Figure 7).

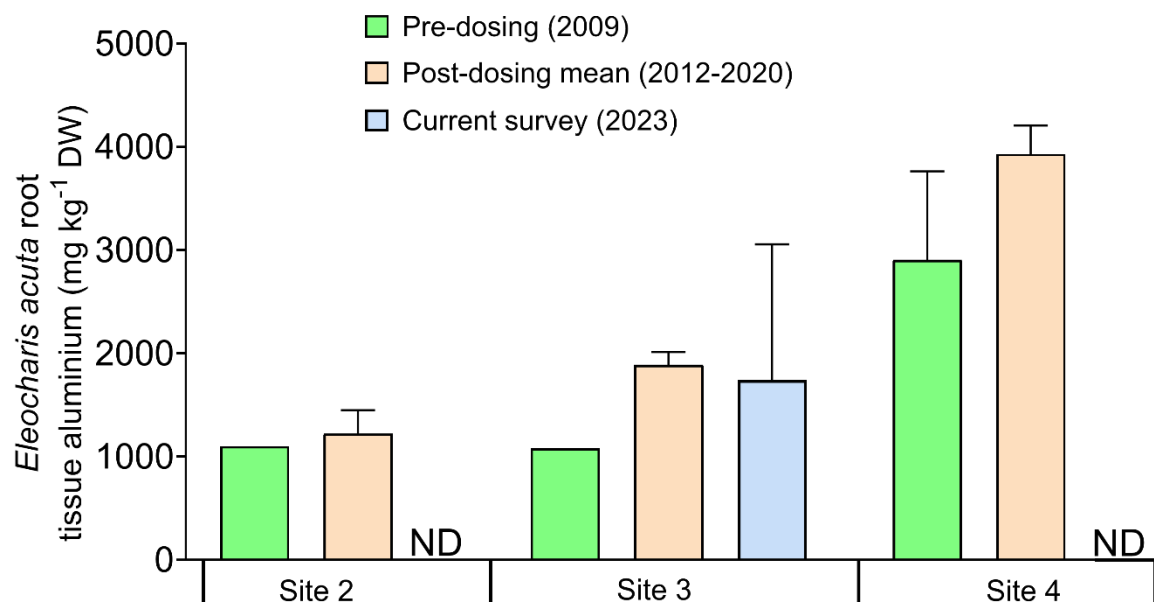


Figure 7. Aluminium concentrations in the roots of the sedge *Eleocharis acuta* (mg kg^{-1} dry weight) from sites within and around Sulphur Bay (geometric means $\pm$ 95% confidence interval). ND = no data.

Discussion

As part of the Bay of Plenty Regional Council's resource consent to dose alum to the Puarenga Stream for phosphorus control, semi-annual surveys of biota from Sulphur Bay and Lake Rotorua have been conducted since 2012. Water samples and tissue samples of *Eleocharis* roots, common bully, kākahi digestive glands and chironomid larvae were taken over two consecutive days in September 2023. Aluminium concentrations in all water samples were lower than the site means of previous monitoring surveys (2012–2020). Similarly, aluminium concentrations measured in chironomid larvae were lower, although only Site 1 was significantly lower than the long-term mean. In comparison, 2023 kākahi digestive gland aluminium concentrations were significantly elevated at Sites 2 and 3 compared to long-term means. Also of note, common bully whole-body aluminium concentrations were significantly elevated at the reference site (Site 4), compared to the long-term mean.

Dissolved aluminium concentrations are naturally elevated within Sulphur Bay due to the geothermal activity. Dissolved aluminium concentrations of $\sim 1 \text{ mg Al L}^{-1}$ were reported by Landman and Ling (2009) prior to the initiation of alum dosing. This concentration is similar to the monthly mean aluminium dose applied to the Puarenga Stream (Ling 2023). However, monitoring data indicates that dissolved aluminium concentrations decrease as the acidic geothermal water exits the bay and mixes with the main body of the lake (Ling 2023; Landman and Ling 2009). During prevailing westerly and north-westerly winds, a plume of geothermal water containing colloidal sulphur can be observed moving eastwards along the southern shore of Lake Rotorua towards Hinemoa Point. In contrast, under easterly and south-easterly conditions, the plume flows in the opposite direction to the west around Motutara Point and into Te Ruapeka Bay (Figure 8). This variability in the geothermal plume explains the consistently high dissolved aluminium levels measured within Sulphur Bay at Site 1, while the other three sites outside Sulphur Bay exhibit lower, more variable concentrations.



Figure 8. Variability in the geothermal plume of water leaving Sulphur Bay. Upper image January 2017, lower image December 2012, Google Earth.

The geothermal water discharge from Sulphur Bay remains the primary factor controlling shoreline benthic ecology in the vicinity of Sulphur Bay. Abell and Hamilton (2015) identified a double gyre system in Lake Rotorua, and the stronger anticlockwise gyre appears to dominate the entrainment of the Sulphur Bay plume (Figure 9). The influence of this plume is clearly discernible in the relative abundance of macrobiota at the sampled sites. The conditions at Site 1 within Sulphur Bay appear to be so harsh that chironomids remain the only benthic organisms able to tolerate such conditions. Kākahi are rarely encountered at Site 2 close to the mouth of Sulphur Bay but are more common at Site 3 and abundant at the reference site (Site 4), which is more protected from the Sulphur Bay plume by Motutara Point. No common bully were caught at Site 2 in 2013 or 2014, but large numbers were caught at this site in 2015, 2016 and 2020 (Ling 2023). This was presumably due to reduced inundation by the geothermal plume, and it is likely that fish move in and out of this area in response to fluctuations in pH caused by the acid waters from Sulphur Bay. Similarly, the presence of *Eleocharis* at sampling sites has been variable, with specimens only occurring at Site 3 in the 2023 survey.

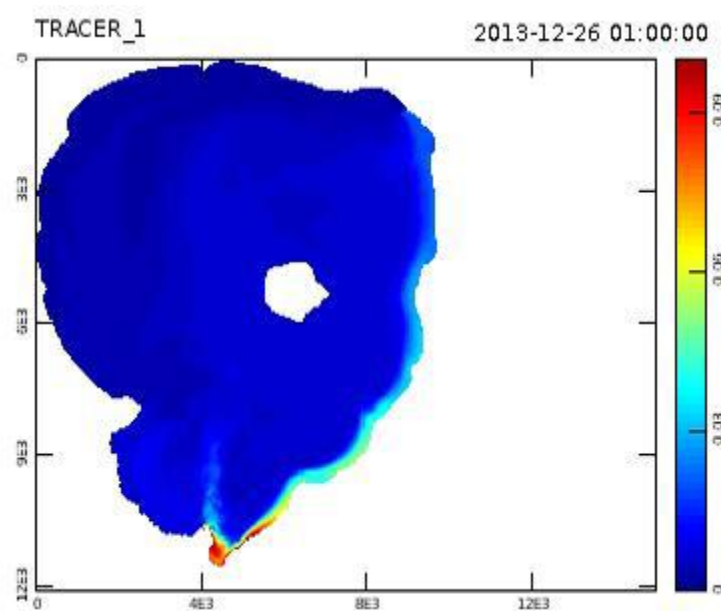


Figure 9. Modelled entrainment of Sulphur Bay water along the eastern shoreline in south-westerly winds (after Abell & Hamilton 2015).

The observed increase in aluminium concentrations in kākahi digestive glands may reflect recent inundation by the Sulphur Bay geothermal plume. As lower pH (i.e., <4) water moves from the head of Sulphur Bay it mixes with lake water and the pH rises above 5.5 (Landman and Ling 2008). This causes the dissolved aluminium in the water to precipitate as aluminium hydroxide, which may be taken up by filter feeding kākahi (Gensemer and Playle 1999). However, significant bioaccumulation of aluminium in secondary tissues via ingestion is likely

to be low, as both vertebrates and macroinvertebrate species are able to effectively excrete particulate aluminium (Clearwater et al. 2014; Wang et al. 2018; Rathinasamy 2025).

Common bully whole-body aluminium concentrations at Site 4 were significantly elevated in 2023 compared to those observed in previous years. This result may not be representative, as previous surveys have not detected elevated tissue concentrations at this site. It is possible that occasional intrusion of the Sulphur Bay geothermal plume into Te Ruapeka Bay coupled with continual alum discharge from the Utuhina Stream may explain the increased aluminium in common bully. Similar concentrations (i.e., $\sim 100 \text{ mg kg}^{-1}$) have been observed in the gill tissue of common bully sampled from just below the alum dosing point in the Utuhina Stream (Tempero and Ling 2026). However, the gill is typically the primary site of aluminium accumulations in aquatic animals and whole-body concentrations of the Utuhina fish are expected to be lower than 100 mg kg^{-1} (Botté et al. 2022; Tempero and Ling 2026). Additional sampling of common bully should be undertaken in Te Ruapeka Bay to determine whether there is a cumulative impact from the Puarenga and Utuhina alum dosing programme or if this was a singular outlying point. In addition, a second reference site outside of Te Ruapeka Bay should be included in future monitoring surveys due to the potential influence of the geothermal plume.

Conclusions

In summary, there was large variation in water column and tissue aluminium concentrations between sites and sampling periods, with water and chironomid larvae tissue aluminium concentrations lower than long-term means. Inversely, kākahi digestive gland aluminium concentrations were greater than long-term means. This variation may be attributed to changes in the direction of the geothermal plume exiting Sulphur Bay which is naturally elevated in aluminium. Further, the risk of bioaccumulation from aluminium ingestion is low as most animals are able to effectively excrete ingested aluminium with minimal transference to secondary tissues. The elevated common bully whole-body aluminium concentrations warrant further investigation to determine if this change is persistent or an outlier to the long-term mean. An additional reference site independent of Te Ruapeka Bay should also be established.

Recommendations

1. Additional one-off sampling of common bully should be conducted in Te Ruapeka Bay to determine whether the elevated tissue aluminium concentrations observed at Site 4 were unusual or persist at this site.
2. An additional reference site located outside of Te Ruapeka Bay should be included in future Puarenga monitoring surveys.

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