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Alum Dosing Effects on Fish and Aquatic Invertebrates: Utuhina Stream 2021-2023

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Cover image: Downstream view of Utuhina Stream at Site 3.

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Executive Summary

To reduce external phosphorus loading to Lake Rotorua, the Bay of Plenty Regional Council has been granted resource consent to dose the Utuhina Stream with alum (aluminium sulphate). Aluminium binds phosphorus, preventing its uptake by phytoplankton and thereby inhibiting growth. Aluminium forms monomeric species outside of circum-neutral pH (pH 6-8), and these species can disrupt osmoregulation and respiration of aquatic organisms. The alum dose rate to the Utuhina Stream is dependent on discharge, with a maximum application rate of 1 ppm aluminium. This report presents the results of an on-going assessment of the fish and aquatic macroinvertebrate communities of the Utuhina Stream for 2021–2023.

Macroinvertebrates, fish and kōura (freshwater crayfish) were sampled annually from one control and two treatment reaches of the Utuhina Stream. Common bully (*Gobiomorphus cotidianus*) were the dominant species of the fish community with juvenile trout and kōaro (*Galaxias brevipinnis*) also captured. Kōura (*Paranephrops planifrons*) were present at all sites but variable in abundance. Interannual variations in site abundance are typical for these reaches of the Utuhina Stream and have been attributed to flood-related disturbances to stream bank morphology and in-stream vegetative cover or physical displacement of fish. No notable effects of alum dosing on stream fish or macroinvertebrate communities were observed between the upstream control site and sites downstream of the alum discharge.

Tissue aluminium concentrations were determined from common bully (flesh, gill, liver) and kōura (flesh, gill, hepatopancreas) by inductively coupled plasma mass spectrometry (ICP-MS). There was some evidence of aluminium bioaccumulation in the gill tissues of common bully at Site 1 in 2021, but overall concentrations were similar to or below long-term averages for all sites and tissues. Kōura flesh aluminium concentrations were elevated above the long-term average at Site 1 in 2021 but concentrations were otherwise similar or below long-term averages across all other tissues and sites. The data presented in this report further supports the conclusion by Ling (2021) that alum dosing does not appear to have a notable effect on the fish and kōura community and that site and interannual variations appear to be due to hydrological and habitat availability.

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Introduction

The water quality of Lake Rotorua has undergone significant eutrophication since the 1960s, with prevalent algal blooms driven by land use change, farm intensification and city sewage discharges (Donald et al. 2019). The Lakes Rotorua and Rotoiti Action Plan (Bay of Plenty Regional Council, 2007) 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. The most recent estimates of phosphorus load to Lake Rotorua put the sustainable phosphorus load to reach a TLI target of 4.2 (in association with the 435 tonnes nitrogen target) between 33.7 to 38.7 tonnes per year (Tempero et al. 2015; McBride 2022). This was similar to the 37 tonnes per year proposed by Rutherford et al. (1989) which was set as a target in the Lakes Rotorua and Rotoiti Action Plan 2009. This requires a reduction in the phosphorus load to the lake of 10–15 tonnes per year or 43–64% of the current anthropogenic phosphorus load (Tempero et al. 2015).

The Utuhina Stream carries an estimated 4.0 tonnes of total phosphorus to Lake Rotorua each year, of which 1.62 tonnes is in the form of dissolved reactive phosphorus (DRP) (Hamill 2022). The Action Plan proposed phosphorus-locking in up to three streams (Utuhina, Puarenga and one other) to reduce 6 tonnes of DRP entering Lake Rotorua using continuous alum (aluminium sulphate) treatment (Bay of Plenty Regional Council, 2007). It was estimated that an alum dosing rate of 1 ppm (1 g m^{-3}) would remove the majority of DRP in the Utuhina Stream. Tempero (2015) assessed the toxicity of this dose rate and concluded that the rate was suitably conservative and unlikely to result in toxicological impacts within the circum-neutral pH range. Alum dosing of the Utuhina Stream began on a trial basis in mid-2006. The Bay of Plenty Regional Council was granted a resource consent in November 2008 for the continuation of alum dosing until 2018. The consent was again renewed in March 2018 and is set to expire in July 2031. Alum dosing of the stream is varied according to stream flow and was occasionally altered in the early years to determine the optimum dose rate to remove phosphorus. Total application of alum to the stream over the treatment period from July 2006 to January 2024 was 589 tonnes, comprising 24.7 tonnes of aluminium per annum (Figure 1).

Alum dosing is widely used for wastewater treatment and restoration of freshwater ecosystems through the removal of DRP, but it is not without risk (Cooke et al. 2005). At circumneutral pH (6–8), common to most surface waters, alum forms aluminium hydroxide ($Al(OH)_3$), a non-toxic white insoluble precipitate which adsorbs dissolved phosphorus, reducing its availability for phytoplankton growth. However, at high (>8.5) or low (<5.5) pH, dissolved monomeric (Al^{3+}) and hydroxy aluminium species occur in varying proportions with respect to acidic (i.e., Al^{3+}, $AlOH^{2+}$, $Al(OH)_2^{+}$) and alkaline (i.e., $Al(OH)_4^{-}$) conditions, with increasing toxicity to aquatic organisms. In aquatic animals, aluminium toxicity is primarily due to disruption of osmoregulation and respiration by dissolved aluminium species at the gills (Alexopoulos et al. 2003; Gensemer et al. 2018) which are the primary site of gas exchange, ion transport, and waste excretion in fish and crustaceans (Playle and Wood 1989).

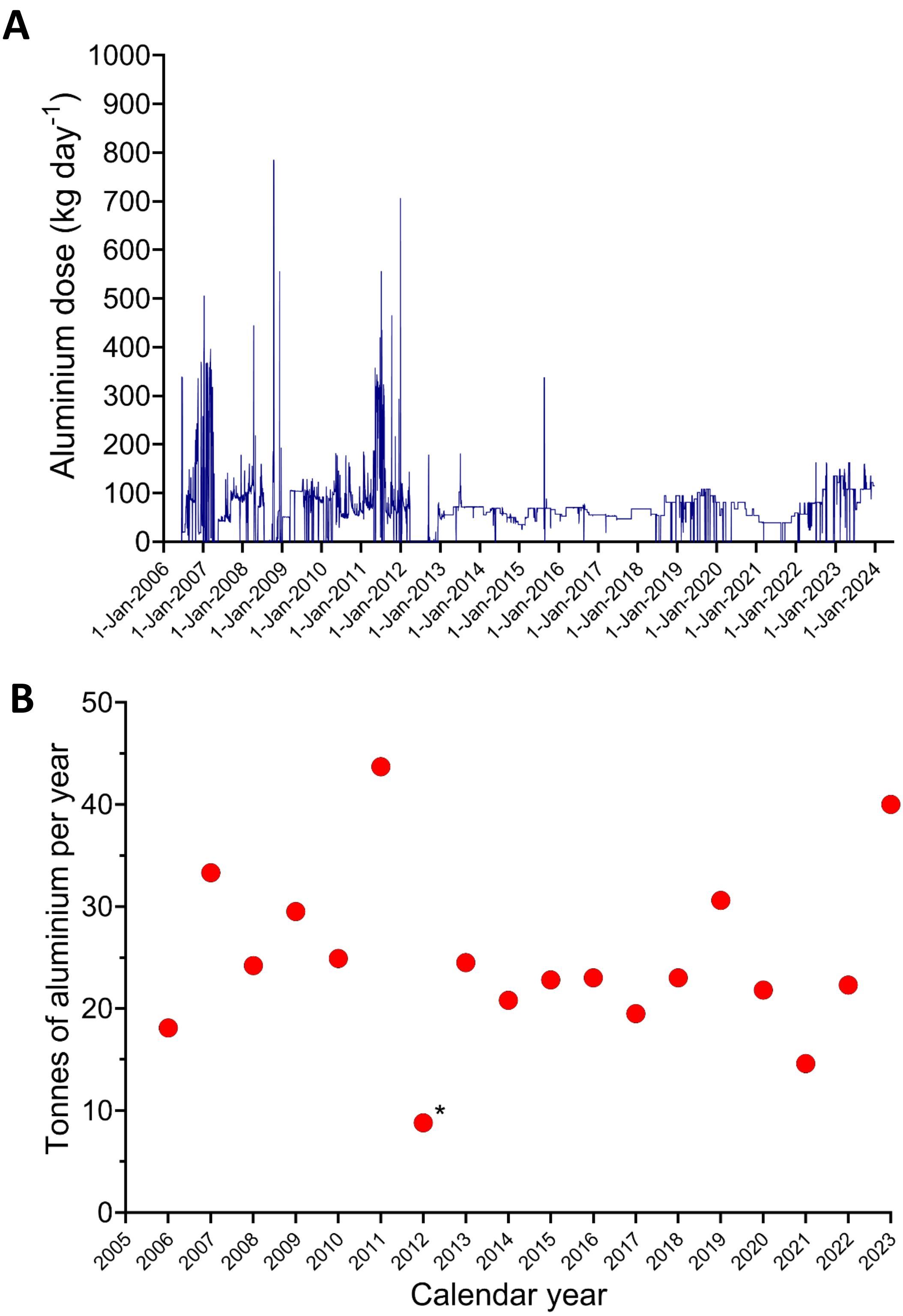

Figure 1. Quantity of aluminium discharged daily (A) and annually (B) to the Utuhina Stream since the commencement of dosing in June 2006. * alum dosing was mostly shut down from 1 July 2012 to 10 December 2012.

The University of Waikato has undertaken annual assessments of potential ecological impacts on the fish and macroinvertebrate communities at an upstream control site and two sites downstream of the of alum discharge point. Evaluation of the bioavailability of aluminium in common bully (*Gobiomorphus cotidianus*) and kōura (freshwater crayfish; *Paranephrops planifrons*) has also been undertaken annually since 2009. Analysis of stream macroinvertebrates has shown no consistent differences between the upstream control site and the sites downstream of the alum dosing (Ling 2021). Some evidence of aluminium bioaccumulation has been observed in the gill and liver tissues of common bully in some years, but there has been no evidence of aluminium bioaccumulation in the tissues of kōura (Ling 2021).

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^2 and a mean depth of 10.8 m (maximum depth 45 m) (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 of 4.2 since 2010 (Donald et al. 2019). The Utuhina Stream is one of nine major inflows to Lake Rotorua draining a catchment of around 60 km^2, with land-use divided approximately evenly between urban, dry stock, bush and scrub, and forestry (Tempero et al. 2015). The stream arises west of Lake Rotorua and flows through residential and industrial areas within Rotorua City where it receives geothermal and stormwater inflows before discharging into lake at Te Ruapeka Bay. The stream becomes highly channelised as it passes through the city, with a mean discharge of 1.85 m^3 s^{-1} at the State Highway 5 bridge (Depot Street) (Wallace 2014).

Fish community survey

The occurrence of fish species, approximate relative density and catch per unit effort (CPUE) were determined for three 50-m reaches of the Utuhina Stream (Figure 2) annually since prior to the commencement of alum dosing in June 2006. Site 1 (control) was 50 to 100 m upstream of the alum discharge in-stream diffuser, Site 2 was 50 to 100 m downstream of the diffuser, and Site 3 was 400 m further downstream in the vicinity of Lake Rd. Relative fish density (total numbers captured) and CPUE (fish captured per hour) were estimated using a two-pass electrofishing procedure according to the method of Landman et al. (2008). A MAF Aquatronics pulsed DC mains set electrofishing machine, powered by a Honda 3-kVA petrol generator, operating at 420 V and approximately 3 A with two hand-held anodes was used to enable simultaneous fishing of each stream side. Two teams of three people performed the fishing while one person remained on the bank for machine operation and safety. Estimates of total fish numbers (absolute density) in this stream could not be calculated from the two-pass removal method as variable and occasionally greater fish numbers are captured in the second fishing passes. Common bully are the most abundant species in the Utuhina Stream and obtaining consecutive reductions in this species using multiple pass electrofishing is difficult. For practical purposes, an estimate of minimum fish density was determined by simply adding the total catch from both passes at each site. Total CPUE and CPUE for each pass at each site could be determined normally based on fish caught and fishing effort (time fishing). All fish and kōura were counted. Captured adult trout were measured or their size estimated if observed, and all fish were returned alive to their respective stream reaches, except for those retained for elemental analysis (see below).

Aquatic macroinvertebrate community survey

Aquatic macroinvertebrate community analysis was undertaken separately to electrofishing but from the same three stream reaches examined for relative fish abundance. Invertebrates were sampled in October two months before electrofishing to avoid effects of electrofishing disturbance. Sampling and analysis were carried out as prescribed for soft-bottomed streams by Stark et al. (2001). Briefly, a 0.5 mm mesh, 0.3 m-wide D-net was used to provide ten replicated 1-m sweeps through representative stream bank habitat, sampling a total area of approximately 3 m^2 at each site. True left and true right banks were sampled and enumerated separately at each of the three stream reaches to provide a value for the macroinvertebrate community index for soft bottomed streams (MCI-sb) according to Stark & Maxted (2007). Samples were preserved in isopropyl alcohol until sorting and enumeration.

Figure 2. Macroinvertebrate and electrofishing sites on the Utuhina Stream including above the alum discharge (Site 1), in the alum mixing zone (Site 2) and upstream of Lake Rd (Site 3).

Tissue analysis

Samples of liver (common bully) or hepatopancreas (kōura), flesh and gills were carefully dissected using acid-washed instruments. A suite of 28 elements was measured in samples based on established methods (USEPA, 1987). Samples were dried at 60°C for 72 hours to constant weight, weighed to the nearest 0.001 mg, and digested using tetramethylammonium hydroxide, heat (60°C) and mixing. The colloidal suspension was then cooled in ice and partially oxidized by the addition of cooled hydrogen peroxide and allowed to oxidize overnight at 4°C. Metals were solubilized by acidification with nitric acid and heating (90°C for 2 hours). After cooling to room temperature, samples were diluted and filtered prior to analysis by inductively coupled plasma mass spectrometry (ICP-MS) by the University of Waikato Mass Spectrometry Facility. All tissue element concentrations were determined on a wet weight basis. Method blanks and matrix certified reference material standards (DOLT and DORM; Canadian Research Council) were run in parallel with all samples. Only results for aluminium are presented here.

Results

Fish community

Common bully (*Gobiomorphus cotidianus*), rainbow trout (*Oncorhynchus mykiss*), kōaro (*Galaxias brevipinnis*) and kōura (*Paranephrops planifrons*), were captured in each of the survey years from 2021 to 2023. In addition, longfin eel (*Anguilla dieffenbachia*) and a 1.14 m shortfin eel (*Anguilla australis*) were captured in 2021 (Figure 3). Common bully were the most numerically dominant fish species each year.

Figure 3. A large shortfin eel (*Anguilla australis*) (approximately 1.14 m total length) captured at site 3 downstream of the alum dosing point in 2021.

Common bully relative density (fish per 50 m reach; Figure 4A) and CPUE (bullies h^{-1}; Figure 4B) varied substantially between years and across sites. However, both measures indicate that common bully abundance is generally lower at the upstream control site (Site 1; long-term averages: 268.9 bullies site^{-1}, CPUE 96.7 bullies h^{-1}) compared to Site 2 (long-term averages: 414.3 bullies site^{-1}, CPUE 137.9 bullies h^{-1}) and Site 3 (long-term averages: 568.8 bullies site^{-1}, CPUE 183.9 bullies h^{-1}), which are downstream of the alum dosing point, although the magnitude of the difference is general stable between years.

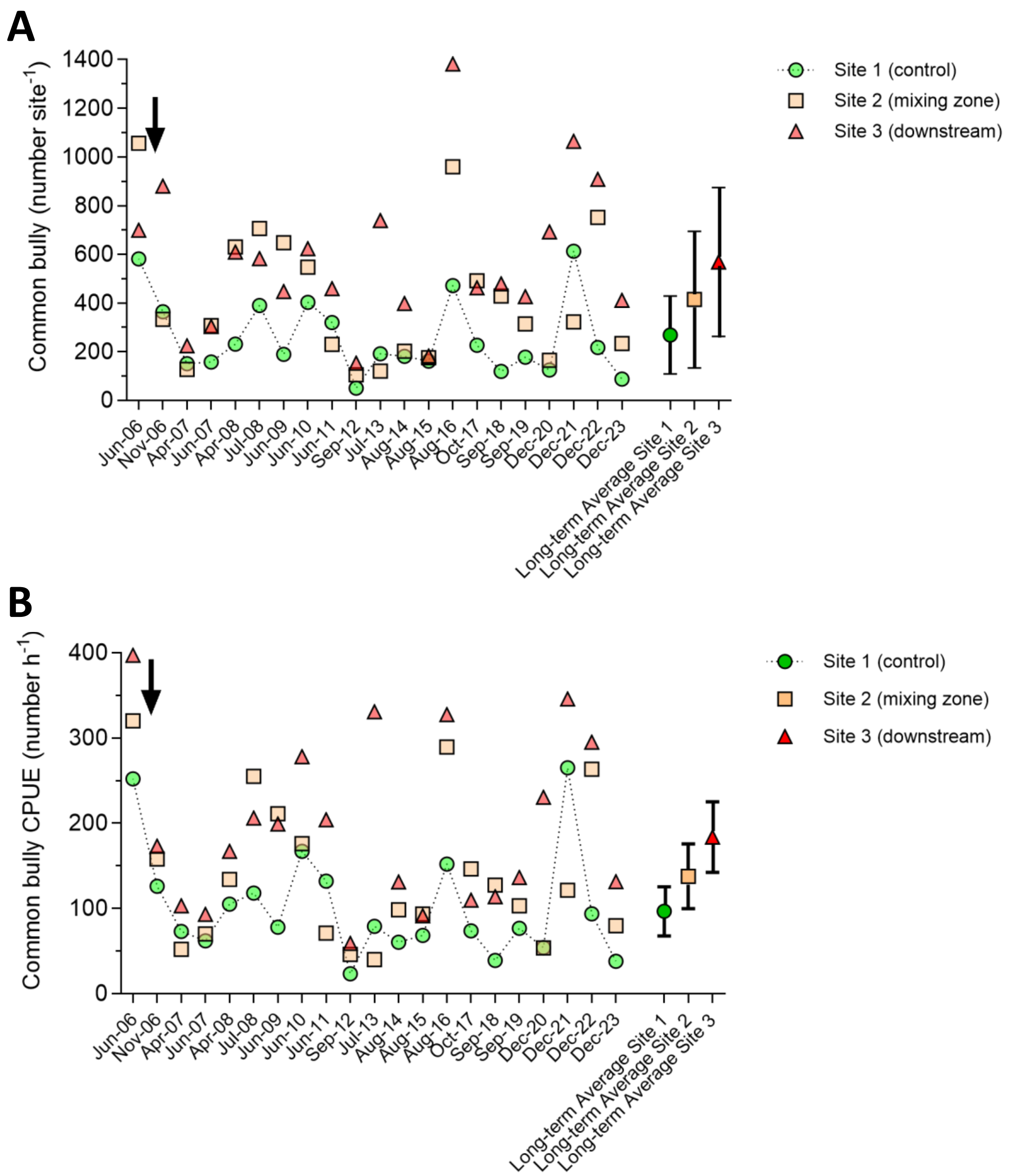

Figure 4. Total numbers captured per site (A) and catch per unit effort (CPUE; B) of common bully in the Utuhina Stream since June 2006. Arrow indicates the commencement of alum dosing in the stream. Values for long-term averages are means ± 1 S.D.

Juvenile trout (young of the year) were always present at all sites in all years. Trout density was almost similar between the upstream control site (Site 1; long-term averages: 28.8 trout site^{-1}, CPUE 10.9 trout h^{-1}) and Site 2 (long-term averages: 31.0 trout site^{-1}, CPUE 10.4 trout h^{-1}), while fish density at Site 3 was slightly lower (long-term averages: 16.2 trout site^{-1}, CPUE 5.9 trout h^{-1}) compared to the long-term average (Figure 5), but numbers varied considerably between sampling dates.

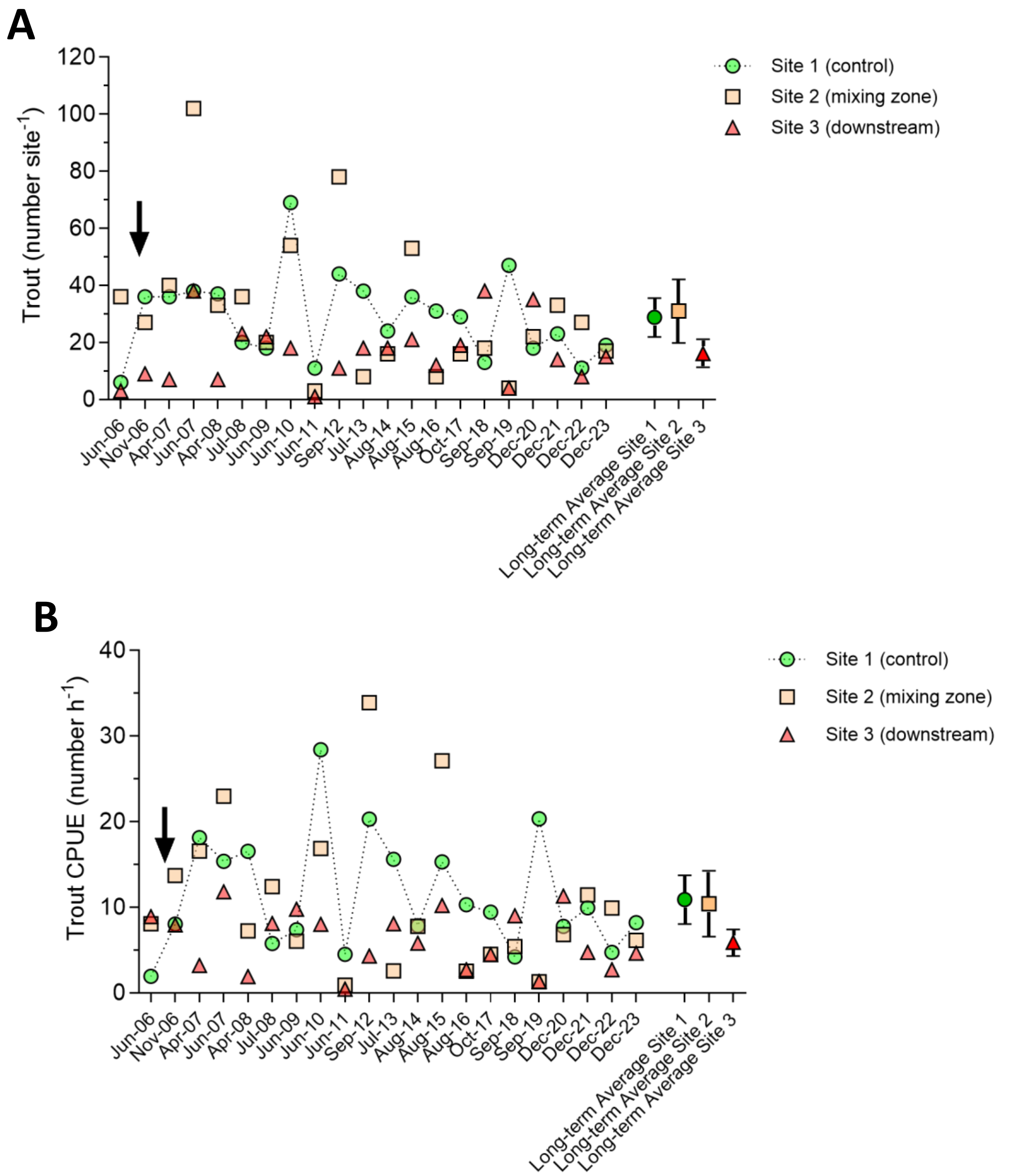

Figure 5. Total numbers captured per site (A) and catch per unit effort (CPUE; B) of trout in the Utuhina Stream since June 2006. Arrow indicates the commencement of alum dosing in the stream. Values for long-term averages are means ± 1 S.D.

Kōura numbers have fluctuated markedly from year to year but were captured at all three sites annually. They are generally least abundant at Site 2 (long-term averages: 12.5 kōura site^{-1}, CPUE 4.1 kōura h^{-1}) and most abundant at Site 3 (long-term averages: 41.5 kōura site^{-1}, CPUE 13.0 kōura h^{-1}) with abundance intermediate at Site 1 (long-term averages: 26.0 kōura site^{-1}, CPUE 9.7 kōura h^{-1}) (Figure 6).

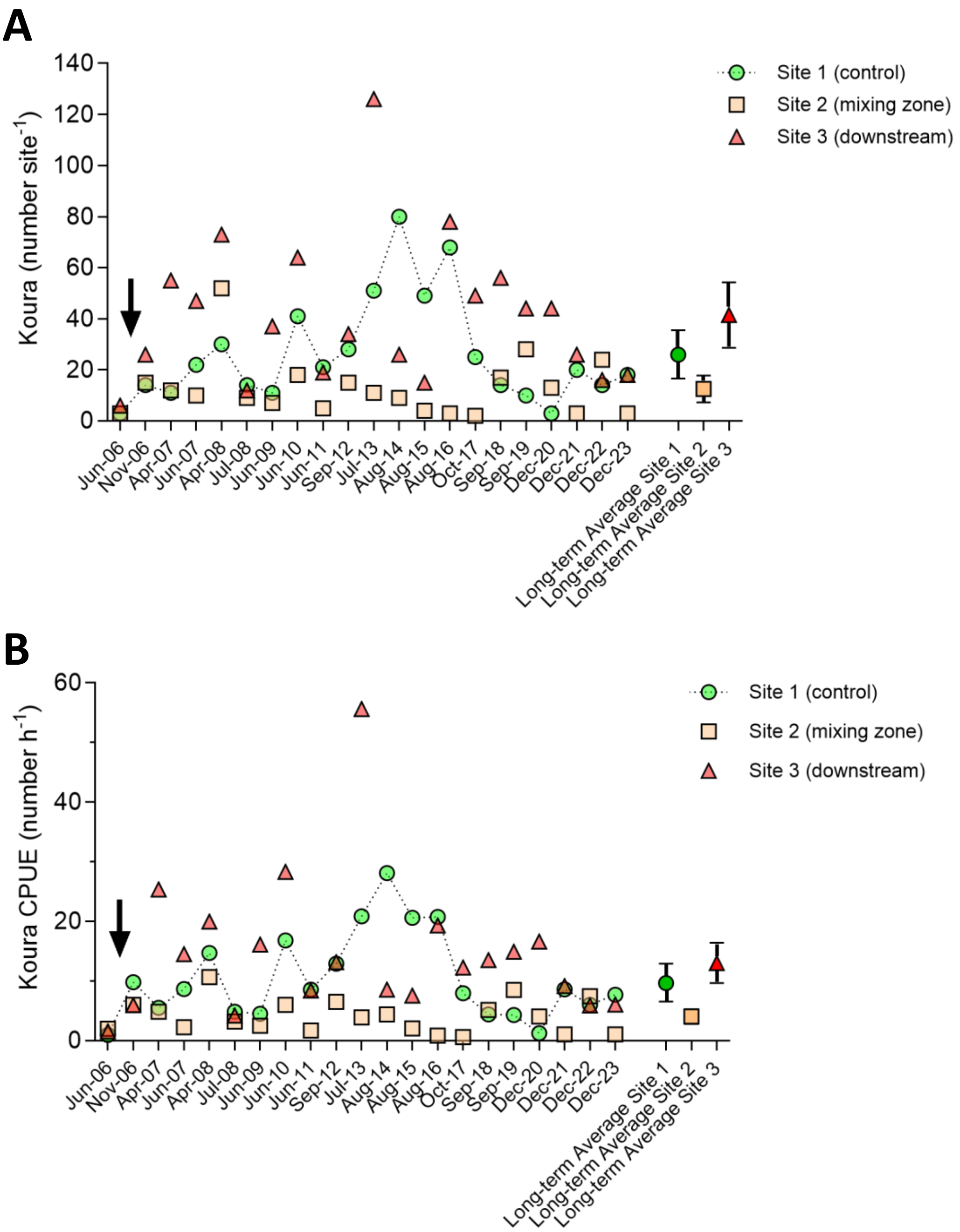

Figure 6. Total numbers captured per site (A) and catch per unit effort (CPUE; B) of kōura in the Utuhina Stream since June 2006. Arrow indicates the commencement of alum dosing in the stream. Values for long-term averages are means ± 1 S.D.

Macroinvertebrate community (MCI-sb)

Semi-quantitative macroinvertebrate community analysis (for soft-bottomed streams; MCI-sb) showed no notable change in the sites for the 2021–2023 period, although the downstream Site 3 typically scored lowest in most years (Figure 7). Values for the MCI-sb index fell within the “fair to good” quality classes of Stark & Maxted (2007) for all three sites, apart from Site 1 in 2019 which scored within the poor range, however, this appears to be anomalous to the long-term trend.

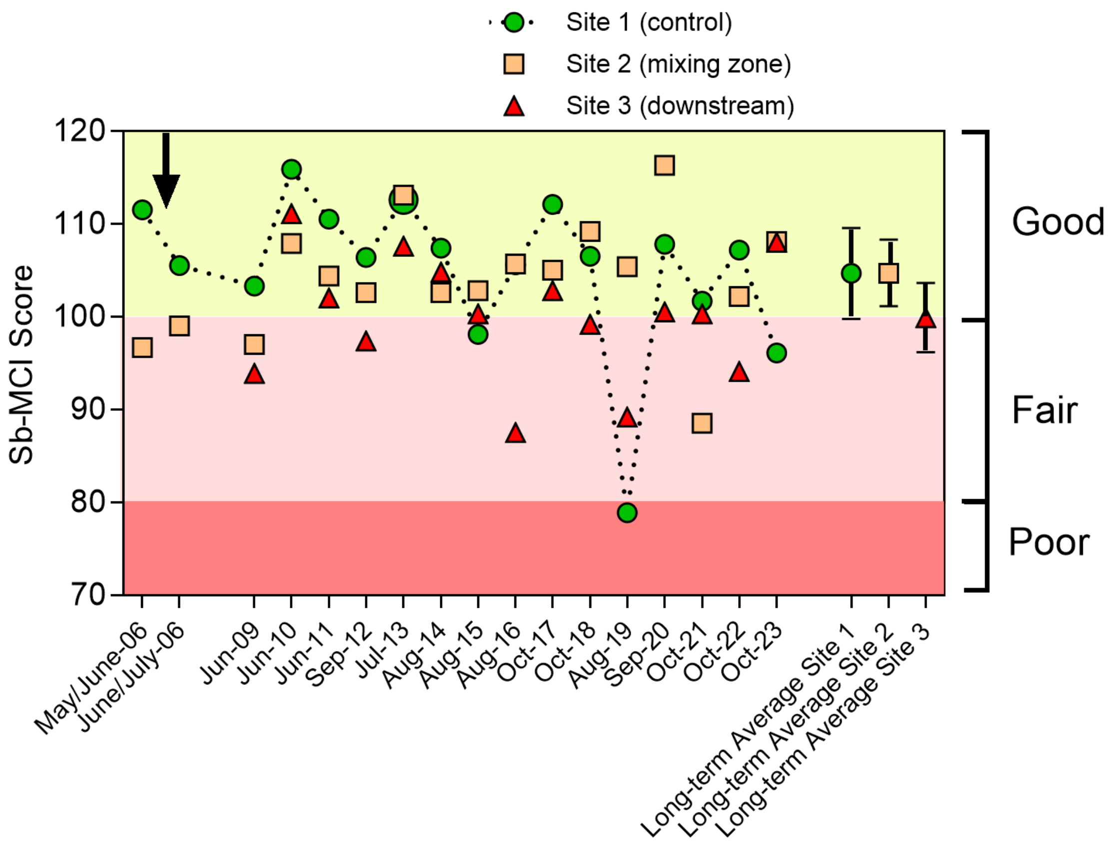

Figure 7. Soft-bottom stream macroinvertebrate community assessment (Sb- MCI) for the Utuhina Stream since June 2006. Values for long-term averages are means ± 95% confidence intervals. Note: values for sites 1 and 2 in 2006 are approximated from data in Clarke 2006.

Tissue aluminium concentrations

Analysis of tissue aluminium concentrations in common bully revealed differences between tissues with the highest concentrations in the gill (2021-2023 mean for all sites 32.7 mg kg^{-1}), followed by liver (2021-2023 mean for all sites 8.3 mg kg^{-1}) and flesh (2021-2023 mean for all sites 0.3 mg kg^{-1}). Tissue concentrations were generally in accordance with previously measured concentrations for the monitored sites, although there does appear to be more interannual variation at Site 1 and Site 2 compared to Site 3. Flesh concentrations were the most consistent across sites while liver concentrations were the most variable (Figure 8).

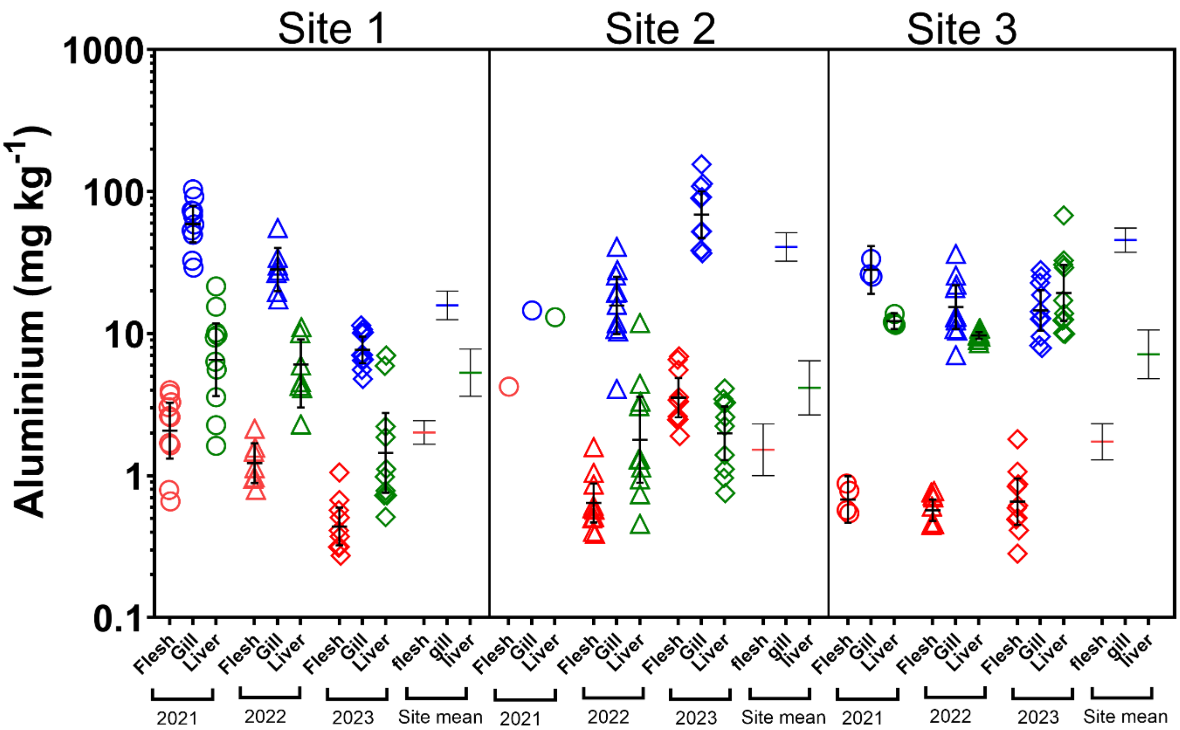

Figure 8. Common bully tissue (liver, flesh and gill) aluminium concentrations (mg/kg WW) for years 2021-2023 and mean tissue concentrations for monitoring years 2009–2020 - geometric mean with lower and upper 95% confidence intervals (CI). Site 1 = upstream control reach, Site 2 = alum mixing zone, Site 3 = downstream reach.

Kōura tissue aluminium concentrations were similar between all three sites, although no specimens of sufficient size for tissue analysis were collected from Site 3 in 2022 (Figure 9). As with bullies, the highest aluminium concentrations were observed in the gills (2021-2023 mean for all sites 34.6 mg kg^{-1}) followed by the hepatopancreas (2021-2023 mean for all sites 34.6 mg kg^{-1}), with the lowest concentrations were in the flesh (2021-2023 mean for all sites 7.5 mg kg^{-1}). There were no notable differences in tissue concentrations in the 2021–2023 data compared to the mean of specific tissue concentrations from previous years (2009–2020).

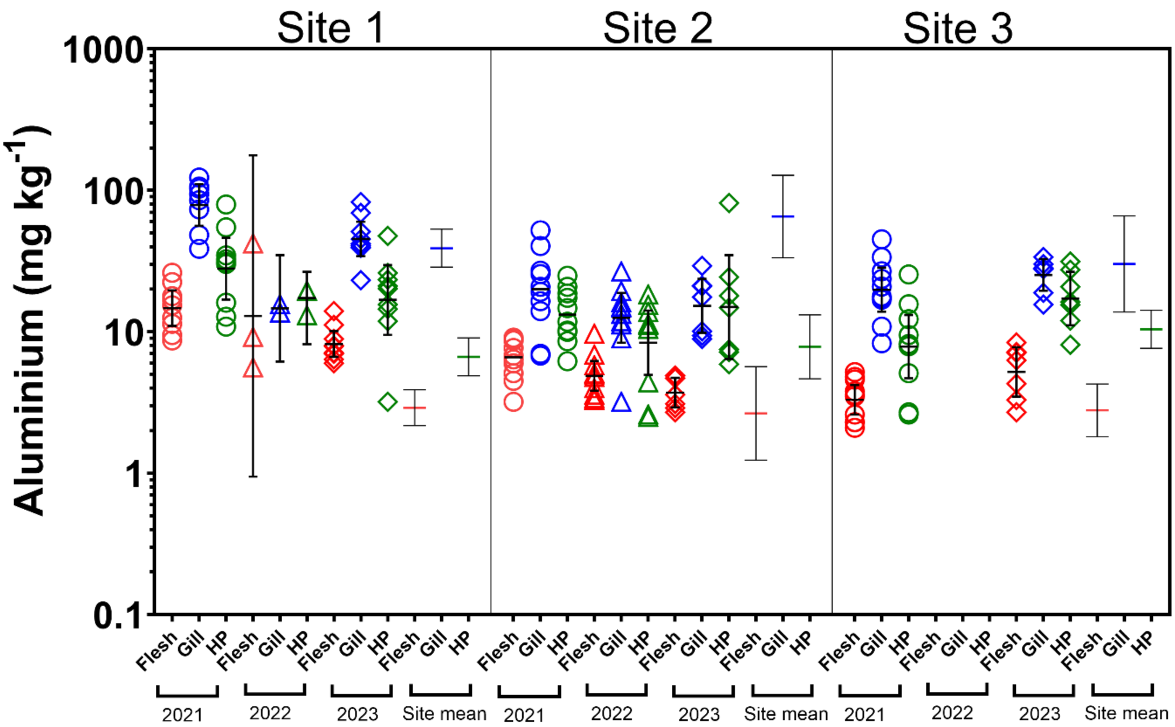

Figure 9. Kōura tissue (flesh, gill and hepatopancreas) aluminium concentrations (mg/kg WW) for years 2021-2023 and mean tissue concentrations for monitoring years 2009–2020 - geometric mean with lower and upper 95% confidence intervals (CI). Site 1 = upstream control reach, Site 2 = alum mixing zone, Site 3 = downstream reach.

Discussion

Annual ecological monitoring for effects of alum dosing to the Utuhina Stream has been conducted since 2006 as part of the Bay of Plenty Regional Council resource consent to discharge alum. Macroinvertebrate and fish community surveys were undertaken annually and aluminium content in the tissues of common bully and kōura were determined through ICP-MS. Macroinvertebrate surveys were conducted at least 2 months before the electrofishing survey in the same stream reaches. Two 50 m reaches downstream of the alum dosing point were surveyed along with one upstream reach as a control site.

Fish community

Eels (*Anguilla* spp.) are not common in the tributary streams Lake Rotorua due to the presence of natural barriers to upstream migration on the Kaituna River (Martin et al. 2007). However, apart from 2020, juvenile kōaro have been captured at every year from 2016 to 2023. Kōaro are a taonga species in the Rotorua Te Arawa lakes and this species suffered a catastrophic decline in abundance following the introduction of trout and smelt in the early 1900s. The observation of kōaro in the Utuhina Stream extends the known distribution of the species in tributary streams of Lake Rotorua. The Utuhina Stream was extensively surveyed in

2007/2008 for the presence of kōaro and none were found (Rowe et al. 2008), their consistent presence in the Utuhina Stream is an encouraging indication that the species may now be established in the stream.

There is typically large interannual variation in fish and kōura CPUE across all three surveyed reaches, much of which can be tentatively ascribed to modification of habitat as the stream is highly channelised as it passes through the city. During major flood events the stream bed becomes highly disturbed as the extent of instream and bankside vegetative cover is limited and significant erosion of the banks has been observed (Ling 2021). Common bully and kōura prefer relatively low flow velocities of around 0.4 $m^3\ s^{-1}$ (Jowett et al., 2008; Jowett and Richardson, 1995) and are likely to be physically displaced by high velocities associated with major flood events. The data presented in this report further supports the conclusion by Ling (2021) that alum dosing does not appear to have a notable effect on the fish and kōura community and that site and interannual variations appear to be due to hydrological conditions and habitat availability.

Macroinvertebrate community

Semi-quantitative macroinvertebrate community analysis (for soft-bottomed streams; MCI-sb) were generally similar to those observed in previous years, although Site 2 was notably lower in 2021 it had improved in 2022 and was above the long-term average in 2023. In addition, Site 3 has typically scored lowest in most years, however, it was also above the long-term average in 2023. Overall, site MCI-sb scores for 2021–2023 were similar to previous years, scoring in the fair to good and there was no pattern of change across the sites that could indicate impacts of the alum dosing on macroinvertebrate community composition.

Tissue aluminium concentrations

Analysis of tissue aluminium concentrations in kōura and common bully were within the range of those observed in previous surveys. There were some differences between tissues with the highest concentrations in gill, followed by liver (hepatopancreas) and flesh. There was some evidence of bully liver aluminium concentrations being higher than at Site 1 over the 2021–23 survey period, however they did not exceed the liver concentration ranges observed for bullies at Site 2 and Site 3.

Although intraspecific variability in the tissue concentrations of non-essential metals is well recognised, it is poorly understood (Pan and Wang 2009). While differences might be expected due to obvious factors such as sex, size, age, diet and metabolic rate, individuals chosen for analysis in this study were selected to be the largest individuals captured on each occasion to reduce some of the influence of such effects. All animals appeared healthy and unaffected by the exposure to alum. Overall, there were no appreciable differences in tissue concentrations between the upstream control site and sites downstream of the alum discharge.

Conclusions

Exposure of macroinvertebrates, fish and kōura in the Utuhina Stream to low continuous alum dosing does not appear to result in changes in community abundance or chronic toxicity. While there was some indication of aluminium accumulation in the gill tissue of fish and kōura downstream of the dosing site this does not appear to affect abundance at downstream sites compared to the control site.

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