WATER QUALITY AND BIODEIVERSITY SURVEY OF THREE WAIOTAPU GEOTHERMAL LAKES

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ABSTRACT

Waikato Regional Council undertook a comprehensive survey of water quality and biodiversity in geothermal Lakes Orotu, Rotowhero and Whangioterangi located within the Waiotapu Geothermal System. The lakes range from 2.6 ha to 4.7 ha in size. To the best of our knowledge, Lakes Orotu and Whangioterangi were surveyed for the first time by boat; previous navigation having been hindered by the terrain, accessibility and the geothermal nature of the water. As part of the survey, samples were collected for analysis of water quality (i.e. nutrient enrichment), geothermal water chemistry markers, phytoplankton and zooplankton community composition, sweep netting of the littoral zone for aquatic invertebrates, fish survey, and vertical profiles of temperature, conductivity, oxygen, chlorophyll fluorescence, pH and photosynthetically active radiation.

All three lakes were acidic with the lowest pH value of 2.8 recorded in Lake Whangioterangi. Water quality assessment based on nutrient concentrations suggests that all lakes were highly nutrient-enriched but showed low primary productivity (i.e. low chlorophyll *a* concentrations). All lakes generally showed low species richness for all surveyed organisms. No phytoplankton and zooplankton were detected in Lake Whangioterangi using standard methodology. Only four eels in poor condition were caught in Lake Orotu with the other lakes being fishless and devoid of submerged macrophytes. Values of the geothermal water chemistry markers were consistent with geothermally influenced lakes, but concentrations of various elements varied considerably between lakes. These lakes are currently not actively managed, however, several anthropogenic pressures may pose a threat to these rare ecosystems and should thus be given more serious regard from a resource management perspective. Vertical profiles of temperature and conductivity in Lake Whangioterangi indicated weak inverse stratification. Due to this profile and its steep-sided bathymetry, we hypothesize that this lake may be classed as meromictic, a rare lake type worldwide. It is envisioned that this hypothesis can be tested with additional monitoring of key in-lake characteristics in the future.

1. INTRODUCTION

Under the Resource Management Act 1991 and the Local Government Act 2002, the Waikato Regional Council (WRC) is responsible for the sustainable management of natural and physical resources in the Waikato Region. These resources include 70 percent of New Zealand's geothermal resources (Figure 1). The Waiotapu Geothermal Field is part of the Waikite-Waiotapu-Waimangu Geothermal System, which is classified in the Waikato Regional Policy Statement 2016 as a Protected Geothermal System, to be managed for the care and protection of geothermal features and their dependent ecosystems.

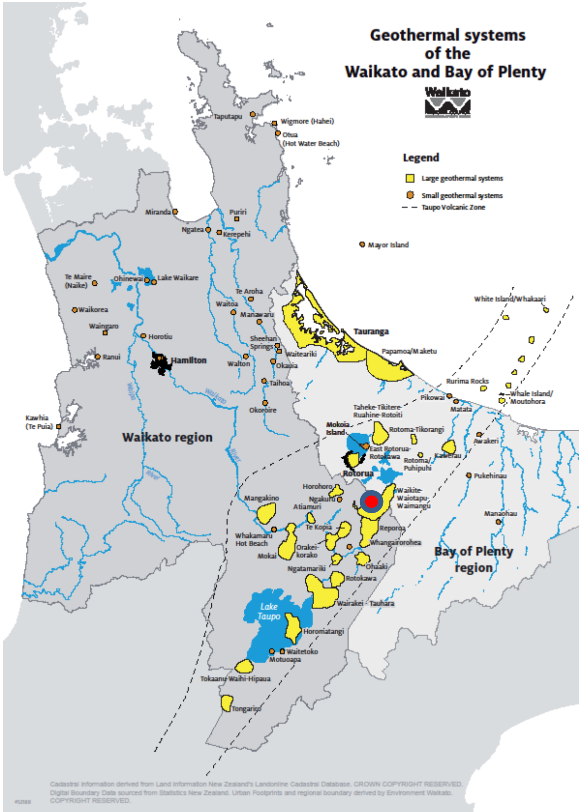

Figure 1: Map of the geothermal systems of the Waikato and Bay of Plenty Regions. The red dot gives the general location of the Waiotapu Geothermal Field

Several lakes in the Waikato region have been defined as 'data deficient', meaning that there is insufficient information known about them to enable an effective classification for prioritising management efforts and interventions (Wildlands 2011). Obtaining general physical, chemical and biological information about these lakes is a priority for assessing and ranking them against other lakes as part of an ongoing process of ranking significant natural areas (SNA), and for identifying potential management actions. To help meet this objective, an investigation was undertaken to fill some existing knowledge gaps for three data deficient lakes located within the Waiotapu Geothermal System; Lakes Orotu, Rotowhero and Whangioterangi (Figure 2).

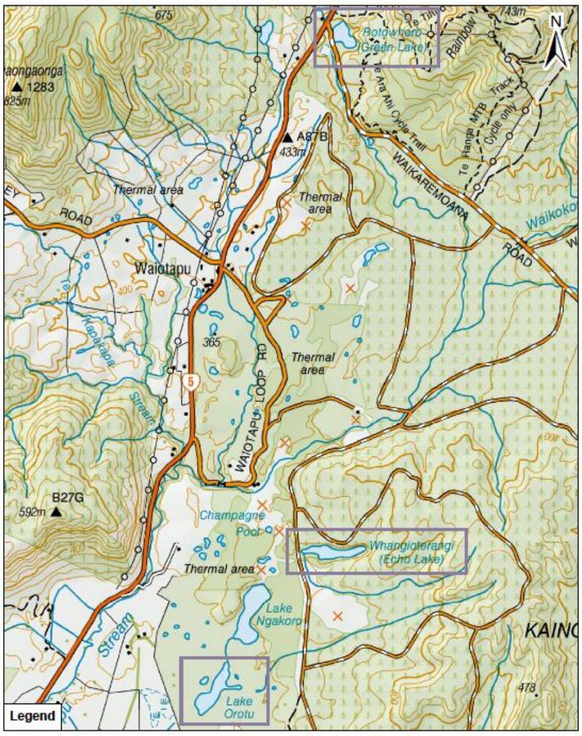

Figure 2: Close-up topographical map of the Waiotapu Geothermal Field showing Lakes Rotowhero, Whangioterangi and Orotu outlined in purple.

2. METHODS

2.1 Lake description

Lake Rotowhero (18.4m depth), also known as Green Lake, is the northern-most of the three lakes, and occupies approximately 2.6 ha at the southern base of the volcanic cone Rainbow Mountain a.k.a. Maungakakaramea, meaning 'mountain of coloured earth' due to the various hues of the active geothermal ground on the mountain. Rotowhero is located at the intersection of State Highway 5 and Old Waiotapu Rd, also known as Waikaremoana Road. The area is owned by the Crown and managed by the Department of Conservation as part of the Rainbow Mountain Scenic Reserve. The lakeshore vegetation consists of areas of geothermally influenced vegetation including prostrate kanuka-mingimingi scrub, Manuka shrubland, and a small patch of Non-vegetated raw soilfield on the eastern side (Wildlands 2014).

Lake Whangioterangi (32m depth) occupies a hydrothermal eruption crater oriented in a West-East direction and 4 ha in area. The sides of the crater are mostly sheer and rise approximately 20 m above water level. The outlet is through a breach at the western end, enabling the lake to drain into the adjacent tourist site, Waiotapu Thermal Wonderland. This breach has been culverted to allow the erection of a forestry road some 50 years ago. The lake and the Wonderland are owned by Ngati Tahu-Ngati Whaoa Runanga Trust and administered as a Scenic Reserve under national conservation laws. The lake is one of the rarest types of geothermal feature, a molten Sulphur-producing spring, there being only three of this type known to the authors, one nearby in the Waiotapu Thermal Wonderland and one off-trail at Yellowstone National Park. This feature type is defined as 'A hot spring whose water supply passes through elemental Sulphur-bearing rock at a temperature sufficiently high to melt the Sulphur (119 ºC) and bring it to the surface' (WRC, 2011).

The land surrounding the lake comprises plantation pine forest. Where vegetation exists on the side of the lake it is either wilding pines, blackberry or a mixture of native species and exotic weeds. A narrow embayment at the outlet is less than a metre deep, having become clogged with sediment brought down by pines falling into the lake, apart from a narrow channel into the culvert. A small waterfall on the north-eastern edge is the only permanent source of surface water into the lake, which has a catchment area of approximately 150 ha.

Lake Orotu (0.9m depth) is approximately 4.7 ha in area and inhabits one of the largest peatland areas in the Taupo Volcanic Zone. It has at least two unnamed streams entering it, one of which drains into its northern point from Lake Ngakoro, which in turn is fed by the outlet from Lake Whangioterangi. The other originates from a large freshwater catchment to the northeast. The geothermally influenced vegetation surrounding the northern quarter of the lake includes Manuka scrub and Raupo-harakeke reedland (Wildlands 2014). The rest of the lake is surround by mature kānuka peatland forest.

2.2 Sample collection

All sampling of the three lakes was carried between 15 and 25 May 2017. Water samples were collected from each lake using a 2.2 litre horizontal Van Dorn water sampler near the lake surface and bottom following protocols outlined in Burns et al. 2000. Water samples were collected from two sites in Lake Orotu, because initial site inspections suggested that the lake may have two distinct basins, one geothermal influenced and one that appeared to display peat lake characteristics due to its tannin-stained appearance, which is common in dystrophic lakes. Aliquot samples were taken for the analyses of nutrient, chlorophyll *a*, and suspended solids concentrations. Additional samples were collected for the analysis of geothermal markers. All samples were stored on ice until analysis.

Phytoplankton samples were collected just beneath the water surface, and transferred to 150 ml polycarbonate jars. Samples were preserved using Lugol's iodine solution and stored in the dark until analysis. Phytoplankton cell counts were carried out at the Cawthron Institute on settled samples in Utermöhl chambers (Utermöhl, 1958) using appropriate identification keys for New Zealand lakes and geothermal water bodies.

Zooplankton samples were collected using vertical hauls through the entire water column with a plankton net (40 µm mesh size; 0.2 m diameter; haul speed ~1 m s^{-1}). Samples were immediately preserved using isopropyl alcohol. In the laboratory at the University of Waikato, preserved samples were examined for zooplankton community composition using appropriate identification keys for New Zealand lakes and geothermal water bodies.

Fish were sampled in each lake using standardised fyke nets and minnow traps. Net dimensions, type and mesh size are described in Joy et al. (2013). A fleet of 8 fyke nets (with exclusion chambers built in) and 16 fine mesh Gee's minnow traps were deployed overnight in each of the lakes sampled. In addition to these nets five 15 mm mesh-size crab traps were also set. Irrespective of lake, two minnow traps were set with each fyke net (one within 5 m on either side of the fyke) and each fyke net was set perpendicular from the lake edge. A wooden pole was used to fix each fyke leader to the lake shore and a single weight was clipped to the cod end to keep the net aligned and submerged on the lake bed. Nets were generally set by boat (and occasionally from the shore if there was a shallow wadeable embayment) and left overnight and retrieved the following day. Upon retrieval, fyke nets and minnow traps were transferred to a shore-based crew who processed all captured fish. Fish were identified, measured for total length and then released. For eels, individuals were anaesthetized using AquiS® to enable accurate identification and measurement.

Depth-referenced (<0.2 m) temperature, conductivity, oxygen, chlorophyll fluorescence, and irradiance data were measured in Lakes Rotowhero and Whangioterangi with a conductivity-temperature-depth (CTD) profiler (SBE 19 plus Seacat Profiler, Seabird Electronics), fitted with a dissolved oxygen and pH (Seabird Electronics) sensor and additional sensors for fluorescence (Turner Designs CYCLOPS-7) and photosynthetically active radiation (PAR; LI-192SA Underwater Quantum Sensor). Vertical profiles in Lake Orotu were recorded with a YSI ProDSS Multi-paramater probe (YSI Incorporated) due to its shallow depth. As part of this study, littoral macro-invertebrates were collected following the methods outlined in David *et al.* (2014), and surveys for marginal vegetation and birds were carried out additionally to bathymetric surveys. Results of these surveys were still pending at the time of writing this manuscript.

2.2.1 Data analysis

The majority of the data collected were summarized using descriptive statistics. Fifteen geothermal water chemistry markers were explored by constructing a Pearson correlation matrix and then by undertaking principal component analysis (PCA). PCA can be applied to multivariate data to identify a small number of transformed variables that describe most of the variation in the data. Analysis of a projection of the two principal components allowed the main relationships between lake chemical variables to be visualized. Data were zero-centered and scaled to have unit variance before the analysis was carried out.

3. RESULTS

All three lakes can be considered highly nutrient-enriched based on observed nitrogen and phosphorus concentrations (Table 1). Extremely high Total Kjeldahl nitrogen concentrations of up to 11.5 g m^{-3} were found in Lake Whangioterangi. Despite high nutrient concentrations, all three lakes showed low chlorophyll *a* concentrations, which is an indicator of algae biomass. Total suspended solids concentration was low in all samples, ranging from 4 to 10 g m^{-3}. Surprisingly, almost all of the suspended solids comprised of suspended solids obtained from the loss on ignition and thus represents the amount of volatile matter present in the solid fraction of the suspended solids. Despite low concentrations of chlorophyll *a* and suspended solids, water clarity, measured as Secchi depth, was low in all three lakes (0.9m in Lake Rotowhero, 0.45m in Whangioterangi, 0.55m and 0.61 in Lake Orotu in the peat and geothermal basin, respectively). Concentrations of chloride, fluoride, reactive silica, sulphate and sulphide varied between lakes but were generally consistent with value expected in geothermal water bodies (Table 1).

The results of PCA (Figure 3) helped to characterize the relationships of geothermal chemical markers between lakes and sites. The eigenvalues of the first two principal components were 2.62 and 2.59 respectively and cumulatively they accounted for 90.76% of the variance in the data that were analyzed. The first component represented on the horizontal axis of the ordination diagram was most strongly loaded with the variables of Thallium (0.38), Iron (0.38), Boron (-0.34), Calcium (0.33) and Mercury (0.32). The second component, represented on the vertical axis, was most strongly loaded with the elements Arsenic (-0.37), Caesium (-0.36), Aluminium (-0.35) and Antimony (-0.35). The lakes were located in different quadrants of the PCA ordination and different sites or depths were generally closely aligned.

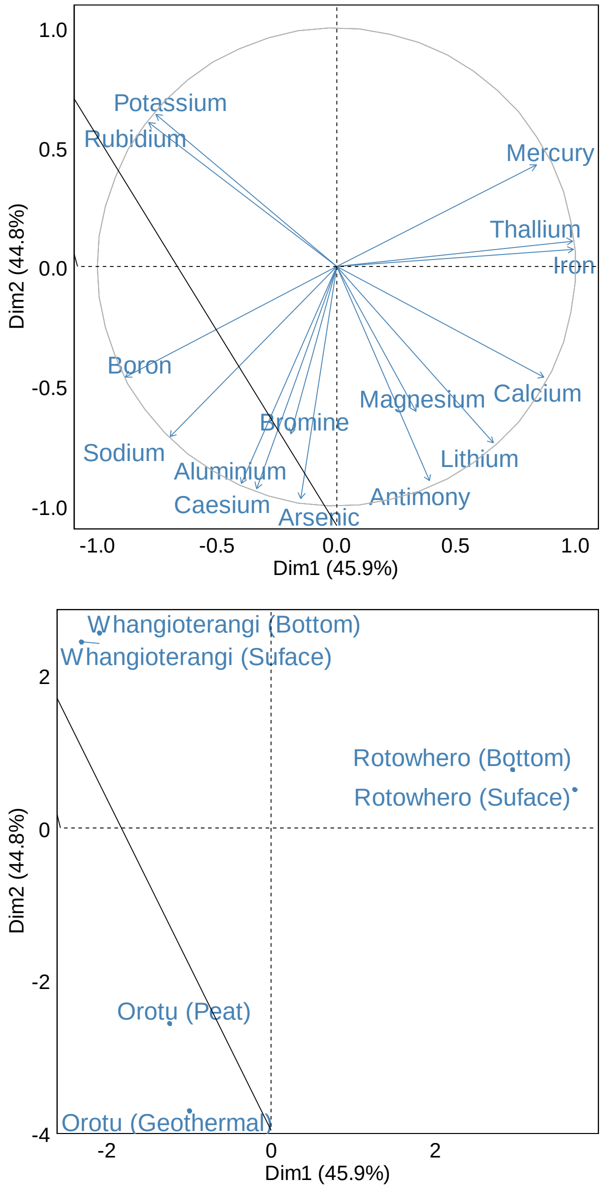

Figure 3. Projection of lake chemical variables on the factor plane (upper panel) and associated ordination diagram for the principal components analysis (PCA; lower panel).

Table 1: Water quality results for samples collected in Lakes Whangioterangi, Rotowhero, and Orotu.

Attribute	Unit	Whangioterangi (surface)	Whangioterangi (bottom)	Rotowhero (surface)	Rotowhero (bottom)	Orotu (peat)	Orotu (geothermal)
Turbidity	NTU	34	51	3.6	3.1	5	5.1
Volatile suspended solids	$g\ m^{-3}$	4	6	6	5	6	9
Total suspended solids	$g\ m^{-3}$	4	6	6	5	10	9
Ammonium	$g\ m^{-3}$	11.1	11	1	1	4.9	5.3
Nitrate	$g\ m^{-3}$	<0.002	<0.002	<0.002	0.003	0.015	0.032
Total Kjeldahl nitrogen	$g\ m^{-3}$	11.4	11.5	1.59	1.57	6	5.6
Dissolved reactive phosphorus	$g\ m^{-3}$	0.088	0.087	0.067	0.058	0.118	0.114
Total phosphorus	$g\ m^{-3}$	0.14	0.147	0.065	0.058	0.098	0.102
Chlorophyll *a*	$g\ m^{-3}$	<0.003	<0.003	0.004	0.003	0.011	0.016
Bicarbonate	$g\ m^{-3}$	104	89	30	29	40	51
Chloride	$g\ m^{-3}$	350	360	171	172	430	440
Fluoride	$g\ m^{-3}$	0.34	0.34	2.8	2.8	1.82	1.69
Reactive silica	$g\ m^{-3}$	220	220	180	181	177	183
Sulphate	$g\ m^{-3}$	310	320	240	240	270	280
Un-ionised hydrogen sulphide	$g\ m^{-3}$	6.5	7.8	<0.002	<0.002	0.032	0.028
Total sulphide	$g\ m^{-3}$	6.1	7.3	<0.002	<0.002	0.03	0.027

No phytoplankton species were found in Lake Whangioterangi using standard methodology. Phytoplankton community in Lake Orotu was dominated by unidentified unicellular algae (< 5 µm) with cell counts of 120,000 and 150,000 cells mL^{-1} in the geothermal basin and the peat basin, respectively. Other taxa recorded in this lake varied slightly between sites and were generally in low number (ranging between 1 and 9 cells mL^{-1}, and 41 unit mL^{-1} for cyanobacteria). These taxa in were cf. *Gloeocystis* sp., *Cryptomonas* sp., *Euglena* sp., *Eunotia* sp., *Navicula* sp., *Nitzschia* sp., *Pinnularia* sp., *Pseudanabaenaceae*, and small unidentified flagellates (< 5 µm). Phytoplankton in Lake Rotowhero was also dominated by small unidentified unicellular algae (< 5µm) with 79000 cells mL^{-1} followed by Picocyanobacteria with 19000 cells mL^{-1}. Other taxa found in Lake Rotowhero showed low numbers and included cf. *Gloeocystis* sp., *Cryptomonas* sp., *Navicula* sp., and *Pseudanabaenaceae*.

No zooplankton species were found in Lakes Rotowhero or Whangioterangi. Previous investigations on Lake Rotowhero have indicated that zooplankton abundance is extremely low, but a few individuals can be found in water samples if collected with substantially more effort (Ian Duggan, pers. comm.). In Lake Orotu, a small number of individuals of the copepod *Paracyclops waiariki* and rotifer *Lecane* cf. *rhytida* were recorded, some unidentifiable bdelloid rotifers and a single individual of a *Cephalodella* species.

No fish were caught in any of the lakes sampled apart from Lake Orotu where four shortfin eels (*Anguilla australis*) were caught in one fyke net (431 to 743 mm TL). Two of these eels were kept as they had died in the net due to anoxic conditions. All of the eels caught were in poor condition (thin) and also appeared to be in various stages of blindness (Figure 4).

Vertical profile data in Lake Rotowhero showed that the temperature in the lake was 31.8 ºC in the surface layer and 31.3 ºC in the bottom waters with a maximum temperature gradient of -1.76 ºC m^{-1} at 0.79 m (Figure 5). While this temperature gradient indicates a reasonably weak stratification, the bottom waters showed lower oxygen saturation (as low as 79.9%) compared to the surface layer (up to 90.9%) with a maximum oxygen gradient of 43% m^{-1} just below the thermocline at 0.91 m. A similar shape of this gradient was also observed in the specific conductance profile but was absent in the chlorophyll fluorescence and pH profile.

Figure 4: Shortfin eel (*Anguilla australis*) captured during this study. Note the opaque eye coloration which indicates blindness.

Vertical temperature profile data in Lake Whangioterangi showed that the lake was inversely (albeit weakly) stratified with temperatures as low as 21.3 ºC in the surface and as high as 22.2 ºC in the bottom waters with a maximum temperature gradient of 4.3ºC m^{-1} at 0.13 m (Figure 6). Dissolved oxygen saturation declined from 5.86% in the surface to 1.26% in the bottom waters with a with a maximum oxygen gradient of 3.14% m^{-1} at 1.94 m. The specific conductance profile also revealed inverse stratification with denser, but warmer, water beneath the thermocline.

Due to its shallow depth, vertical profiles in Lake Orotu were recorded using a YSI ProDSS Multi-paramater probe. Lake Orotu was the coldest lake of the three lakes surveyed with temperature as low as 13.4 ºC in the 'peat' basin and up to 17 ºC in the 'geothermal' basin. Temperature readings in the bottom water of the geothermal basin suggests that the lake was stratified (bottom water temperature of 15.6 ºC), which also resulted in a decline of oxygen saturation of 40.8% in the surface to 25.1% in the bottom.

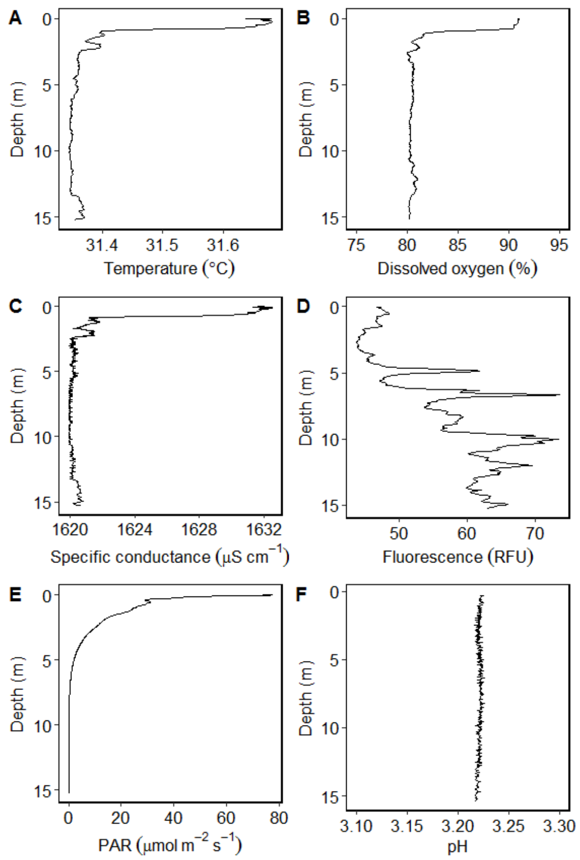

Figure 5: Vertical profiles of (A) temperature, (B) dissolved oxygen saturation (C) specific conductance, (D) chlorophyll fluorescence, (E) photosynthetically active radiation (PAR), and (F) pH in Lake Rotowhero.

DISCUSSION

A comprehensive survey was carried out of water quality (including geothermal water chemistry markers) and biodiversity in geothermal Lakes Orotu, Rotowhero and Whangioterangi, which are located within the Waiotapu Geothermal System. All lakes were highly nutrient-enriched but showed low primary productivity. Biodiversity surveys have revealed low species richness for all survey organisms, with some organisms being recorded as absent using standard methodology.

The zooplankton species found in this survey are largely consistent with taxa found in other geothermally influenced lakes in the central volcanic plateau (Duggan & Boothroyd 2002). It is noted that Lake Rotowhero has been sampled for zooplankton in previous studies (Lewis 1974; Duggan & Boothroyd 2002), which have indicated that abundance of zooplankton can be highly variable and generally extremely low in this lake type. Thus, results from present survey with regards to taxa richness using standard monitoring methodology should only be regarded as indicative.

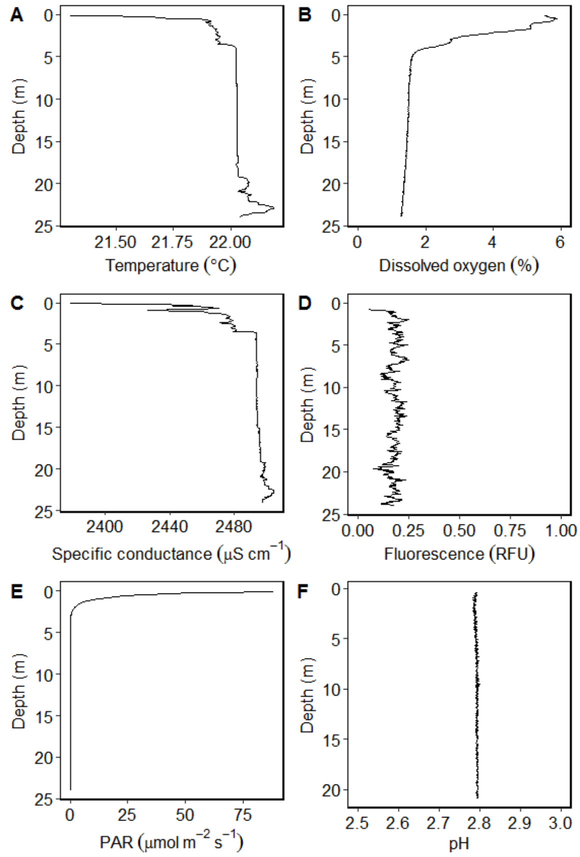

Figure 6: Vertical profiles of (A) temperature, (B) dissolved oxygen saturation (C) specific conductance, (D) chlorophyll fluorescence, (E) photosynthetically active radiation (PAR), and (F) pH in Lake Whangioterangi.

Anecdotal evidence has suggested that all of these geothermal lakes were fish-less. It is likely that environmental constrains in these lakes (mainly low pH and oxygen content and high temperature and conductivity) can explain the absence of fish in Lakes Whangioterangi and Rotowhero. Yet, *Anguilla australis* was found in Lake Orotu and it remains unclear how this species arrived in the lake. The lake drains into the Waiotapu Stream and ultimately into the Waikato River. However, given the lake's distance to the coast (>250 km) and the presence of at least 6 downstream Waikato river hydro dams, illegal release of these individuals rather than unassisted migration may be more likely. Otoliths (fish ear stones) were removed from two dead fish found during this survey. These structures will be used to determine the age of these fish and analysed for trace elements to investigate their potential life-history movement.

Phytoplankton community diversity in Lakes Orotu and Rotowhero were low and numerical abundances were dominated by unidentified pico- and nanoplankton. There are several survival strategies that the species within these groups would have to employ to overcome the extreme environmental conditions observed in the lakes. For example, at pH values <4, inorganic carbon may be limiting, and mixotrophic, low-light strategists may be able to metabolise alternative sources of carbon (Jones, 2000). Another important functional trait may be related to motility in order to enable phytoplankton to migrate into metabolic favourable layers of the water column.

Table 2: Vertical profile data for Lake Orotu.

			Depth				
Site	**Attribute**	**Unit**	**0m**	**0.2m**	**0.4m**	**0.6m**	**0.8m**
Peat	Temperature	ºC	13.4	13.4	13.4	-	-
	Dissolved oxygen	%	43.3	40.2	39.6	-	-
	Specific conductance	$\mu S\ cm^{-1}$	2460	2466	2472	-	-
	pH		3.01	3.01	3.01	-	-
Geothermal	Temperature	ºC	17	17	16.5	15.5	15.6
	Dissolved oxygen	%	40.8	36.1	30	25.6	25.1
	Specific conductance	$\mu S\ cm^{-1}$	1930	1951	2394	2587	2592
	pH	-	3.6	3.29	3.08	2.95	2.95

Mixing patterns in these geothermal lakes may be influenced by a variety of factors. For example, stratification in Lake Rotowhero has been found to be driven by convection and wind, despite geothermally-driven mixing and disruption of stratification (Brookes et al. 2013). In Lake Orotu, thermal stratification may be predominantly driven by diurnal changes in solar radiation due to its shallow depth. There was also some evidence to suggest that the 'geothermal' basin may be more influenced by geothermal heat inputs that the southern 'peat' basin.

Thermal structure in Lake Whangioterangi suggested that the lake was inversely stratified, which can be largely explained by the increases in conductivity (i.e. high concentration of dissolved salts) in the bottom waters. It is noted that the concentrations of geothermal water chemistry markers in this lakes was not substantially different in the surface and bottom water sample (see Figure 3). This was due to the water sampling protocol which would have missed the relatively thin layer in the surface (maximum temperature gradient was recorded at 0.13 m). Based on the lake's basic characteristics, however, we can hypothesize that Lake Whangioterangi may be classed as meromictic, a previously undocumented lake type in New Zealand. Meromixis occurs when mixing energy is insufficient to homogenise the water body completely. Generally, this phenomenon results in chemical gradients that often produce unfavourable conditions for biota in deeper waters (Boehrer et al. 2017). Common features of meromictic lakes are a relatively disproportionate depth compared to surface area, and a deep water layer that is denser than the surface layer, often due to increased salinity. These features are certainly consistent with observations in Lake Whangioterangi. Other chemical and biological features of meromictic lakes can vary substantially between lakes (Schultze et al. 2017; Zadereev et al. 2017), rendering their classification difficult based in these criteria (particularly based on results from a single survey). Testing our hypothesis will require detailed monitoring of thermal structure, heat budgets and chemical composition over prolonged periods of time. Of upmost importance in this context may be an investigation into the effects of the culvert that currently drains the lake, on the heat budget and chemical composition of the thin surface layer.

Because of their unusual water chemistry and influence of geothermal activity, geothermal lakes' ecosystem functioning, including organic matter breakdown, primary productivity nutrient recycling, and metabolism, is very different to that of other lakes types,. Thus, these lakes require careful consideration for active management which is often aimed at reducing or mitigation the impacts of nutrient enrichment and invasive flora and fauna on ecosystem dynamics. Clearly, implementing management options towards reducing the effect of nutrients on ecosystem functions in geothermal lakes will be unnecessary. Instead, management should involve careful considerations for water levels and heat budgets, for example through appropriate design of culverts. Notwithstanding large knowledge gaps of these severely understudied ecosystem types, our survey highlights the unique nature of these lakes and thus all active management should ideally be focused towards maintaining and protecting the natural characteristics of these systems that remain largely undistributed.

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