Geothermal Lakes and Pools of the Waikato Region, New Zealand

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ABSTRACT

This paper, abridged from a chapter in a forthcoming book, (Özkundakci et al., in press, 2022), describes the major geothermal lakes and pools in the Waikato Region in terms of their setting, physical characteristics, geomorphology, geochemistry, and invertebrate and microbial ecology. It draws on research on Waikato geothermal lakes published from the 1950s to 2022.

1. INTRODUCTION

New Zealand is alive with active volcanoes, geothermal systems and moving faults that cause earthquakes. Most of the nation's geothermal and volcanic resources are situated in the Taupō Volcanic Zone (TVZ), a band of active volcanism that stretches from Mount Ruapehu in the southwest to Whakaari (White Island) in the northeast, and beyond on a rifting-arc environment (Wilson et al., 1995; Wilson and Rowland, 2016). Much of the TVZ falls within the boundary of the Waikato Region, and consequently the Region is home to approximately 70% of the nation's geothermal resource (Figure 1).

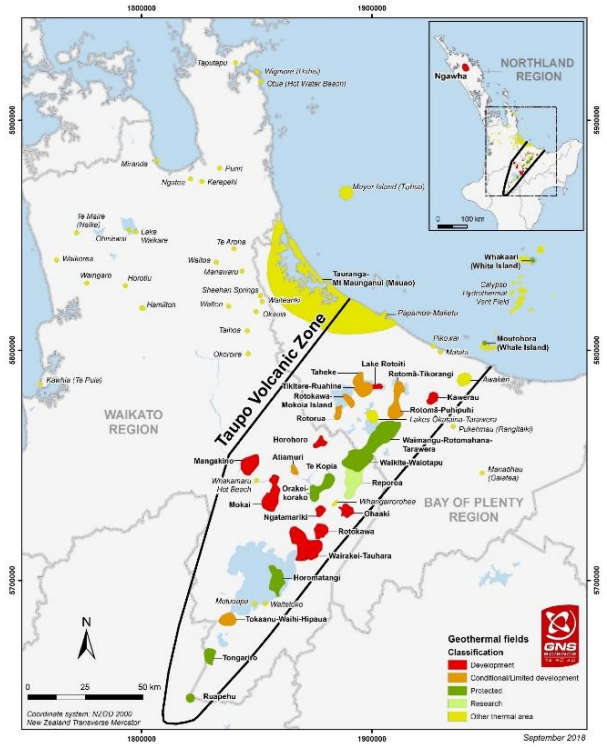


Figure 1: Taupō Volcanic Zone showing regional boundaries and geothermal systems. Image courtesy of GNS and NZ Geothermal Association.

Most of the Waikato Region's geothermal resource is located in fifteen discrete areas of geothermal activity known as geothermal systems. Each geothermal system has many active geothermal features such as steaming ground, interconnecting aquifers, fumaroles, boiling mud pools, sinter terraces, hot springs, lakes, and geysers. Associated with these features are unique ecosystems providing habitat for extremophilic microbes, invertebrates and plants that depend on the extremes of heat and water chemistry found in geothermal locations.

Māori legend and oral histories describe many essential elements of this geological setting in the legend of the ancestor Ngatotoirangi (Waikato Regional Council, 2011). The Māori term for geothermal hot springs and pools is Ngāwhā, and such features have traditionally been used by Māori for cooking, bathing, healing, timber preparation and ceremonial purposes.

There are five geothermal lakes larger than one hectare (ha) in the Waikato Region. Four of them are in the Waiotapu Geothermal System, near each other. They are Lakes Rotowhero, Whangioterangi, Ngakoro and Orotu. The fifth, Rotokawa, is in the Rotokawa Geothermal System and is New Zealand's largest geothermal lake with an area of 65.4 ha (Wildlands 2015). There are many more geothermal lakes and pools smaller than one hectare dotted throughout the part of the TVZ that is within the Waikato Region.

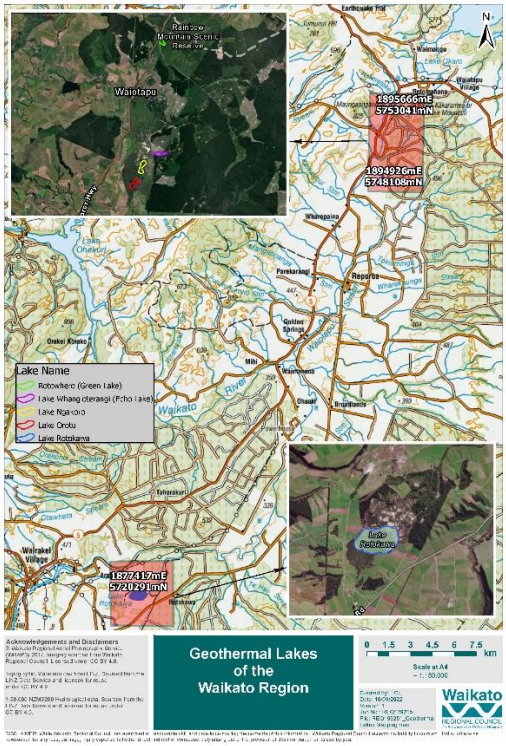


Figure 2: Geothermal Lakes of the Waikato Region.

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2. GENERAL SETTINGS OF THE WAIKATO GEOTHERMAL LAKES

2.1 Waiotapu Geothermal Field

The Waiotapu Geothermal Field, which is part of the Waikite-Waiotapu-Waimangu Geothermal System, has its northern boundary approximately 21 kilometres southeast of Rotorua. It has New Zealand's largest area of active geothermal ground, stretching 7.2 km from Maungakakareamea in the north to the southern tip of Lake Orotu in the south. Within it are hundreds of geothermal surface water features, including four of the five geothermal lakes occupying more than 1 ha in the Waikato Region; and one of Region's two largest geothermal pools, Champagne Pool, which is New Zealand's most photographed geothermal feature, and an important tourist feature.

Three of Waiotapu's geothermal lakes are connected by streams: Whangioterangi drains into Ngakoro, which drains into Orotu. Rotowhero, Whangioterangi and Ngakoro occupy hydrothermal eruption craters (Lloyd, 1959) and contain geothermal water. In marked contrast, Orotu is a shallow peat lake with a maximum depth of 0.6 m (See Table 1).

2.1.1 Lake Rotowhero

Lake Rotowhero, the northernmost of the Waiotapu geothermal lakes, lies at the southern base of Maungakakareama (Rainbow Mountain) within the Maungakakaramea Scenic Reserve and is 2.9 ha in size. The maximum measured depth is 18 m at the site of a major upwelling; however, more detailed bathymetric measurements at that site are likely to obtain even deeper readings in the vent. The water's pH is 3.2 and its temperature is generally around 31.5 °C, although there are two sections of the lake that have geothermal inputs that are warmer. One of these is beside Kerosene Creek Road and the other is on the opposite side of the lake, where a warm stream enters the lake after traversing steaming ground. The catchment area of 1101 ha includes the native bush reserve of Maungakakaramea, and forestry and farmland across the highway. Native vegetation covers 7.2% of the catchment (Wildland Consultants Ltd., 2011) (See Table 1).

2.1.2. Lake Whangioterangi

Lake Whangioterangi (Figure 3) occupies a long narrow hydrothermal eruption crater in a west-east orientation, with sheer sides of approximately 20 metres height from water level to ground level. Its drainage point is a breach in its wall at the western end, and from there a stream takes its outflow into Ngakoro. Whangioterangi is 3.6 ha in area and is at least 32 metres deep at its deepest point, where deep geothermal springs feed into the lake (See Table 1). These include molten sulphur-producing springs, which bring dissolved sulphur from depth. The sulphur then coagulates into floating elemental grey globules of up to 1 centimetre in diameter as it cools. The smaller suspended sulphur particles give the lake water its characteristic grey appearance. Molten sulphur-producing springs are very rare worldwide. Only two others are known of, one at the nearby tourist area Waiotapu Thermal Wonderland (Lloyd, 1959), and one in a remote area of Yellowstone National Park, USA (Keam et al., 2005).

Aquatic fowl are found at the lake, and it is visited by duck shooters for that reason. Whangioterangi's catchment area of 4.5 ha consists of mostly flat to gently contoured plantation pine forestry. There is little native vegetation surrounding the lake, and it has only 5.9% native vegetation cover in its catchment (Wildland Consultants Ltd., 2011). Large numbers of wilding pines have grown up near the lake edge and subsequently fallen in, causing a log jam at the outlet. This may have altered the natural water chemistry of the lake, as evidenced by a very high total Kjeldahl nitrogen count (Catlin et al., 2017), which is unusual for a geothermal lake, and indicates significant organic matter being present in the water. Whangioterangi is part of the Waiotapu Scenic Reserve, but as it is surrounded by plantation forestry, access is restricted.



Figure 3: Lake Whangioterangi.

2.1.3. Lake Ngakoro

Lake Ngakoro is a 7-ha lake within the Waiotapu Thermal Wonderland, a geothermal tourism park with Scenic Reserve status. The lake receives geothermal water from other geothermal features within the park, mixed water from Whangioterangi, and fresh water from its catchment area of 235 ha. The immediate surrounds in the park are native bush, accounting for 37% of the catchment, while the rest is plantation forestry (Catlin et al., 2017). There is no road or track access to Ngakoro; therefore, no boating access to it other than perhaps a lightweight kayak that could be carried manually through the park. The lake has been little studied in recent years, as a consequence. However, Lloyd (1959) described and mapped numerous alkaline chloride sinter-forming hot springs around the lake margins ranging in temperature between 80.0 °C and 98.5 °C (See Table 1). Hedenquist (1991) also kayaked on the lake and took measurements off some hot springs there (Mann et al., 1986).

2.1.4. Lake Orotu

Lake Orotu (Figure 4) occupies approximately 4.7 ha and has a maximum depth of 0.8 m See Table 1. It is part of a Wildlife Management Reserve (Government Purpose) (Wildlands, 2015). Orotu is quite different from the other three geothermal lakes at Waiotapu. The reserve occupies flat peaty soils primarily vegetated by mature kanuka forest, which is a rare occurrence as kanuka normally acts as a nursery crop for taller and longer-living species. Orotu could be considered a peat lake as its water is turbid brown due to the tannin concentration typical of peat lakes (13). Ngakoro discharges geothermal water into Orotu's northern end, and near the Ngakoro discharge point there are geothermal springs adding to the lake's geothermal character. A

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freshwater stream enters from a pine plantation in the northeast.

Orotu's catchment of 582 ha includes those of Whangioterangi and Ngakoro. Peatland reserve surrounds the lake beyond that are sheep and dairy farms. A small, barely flowing stream with an almost flat gradient exits at Orotu's southern end and joins the Waiotapu River near Campbell Road. There are no formal roads or paths to the lake, but a narrow informal path gives access for duck shooters. Also, small boats can be carried in to access the 10 to 15 maimai (hunting huts) on the lake.

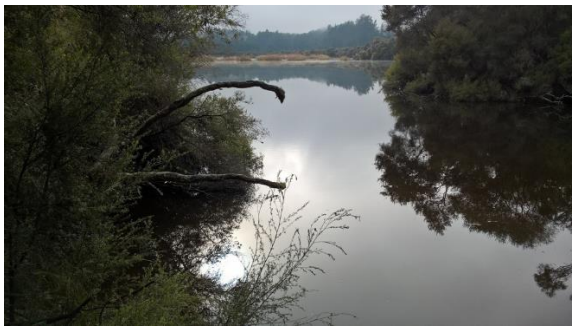


Figure 4: Lake Orotu.

Orotu is the only geothermal lake in the region and New Zealand known to support fish. Four short-finned eel specimens collected in 2017 were of poor health and it is postulated that they had been stocked there rather than existing at the site naturally, although they could have entered via the outlet or the non-geothermal inlet (Catlin et al., 2017).

2.1.5 Geothermal Pools on Waiotapu Geothermal Field

In addition to the lakes described above, there are approximately 80 geothermal pools on Waiotapu Geothermal Field, comprising a total of 9.6 ha (Wildland Consultants Ltd., 2015). About 30 of these range between 0.1 ha and 0.5 ha; the rest are smaller. The most famous and spectacular is the Champagne Pool in the Waiotapu Thermal Wonderland, which is just under 0.2 ha. It is an alkali-chloride pool occupying a deep hydrothermal eruption crater. The gas bubbles uprising from depth in many locations are reminiscent of a glass of champagne, giving the pool its name. Thermophilic microorganisms give the pool edges their striking orange colour. White sinter formations are actively created around the rim of the pool by these microorganisms as they take silica from the water as it cools (Hetzer et al., 2007).

2.2 Rotokawa Geothermal System

Lake Rotokawa (Figure 5) occupies a hydrothermal eruption crater on the Rotokawa Geothermal System approximately seven kilometres northeast of Taupō. It is New Zealand's largest geothermal lake, occupying 64.5 ha (Wildlands, 2015). It has a maximum recorded depth of 27 metres (Forsyth, 1997) and a catchment area of 1090 ha, which is mainly farmland and plantation forestry. The lake is surrounded on the northern side by the Lake Rotokawa Conservation Area, whose vegetation is mainly geothermal. Geothermal springs and a large geothermal lagoon discharge into the lake here. The lake has a substantial wetland on its southwestern side. The lake outlet is the Parariki Stream which flows from the eastern side northwards to the Waikato River. The stream has many geothermal springs and seeps entering it along the way.

The water of the lake has a temperature of 23 °C and a pH of 2.1. The lake edge provides a breeding ground for the critically endangered black-billed gull and the nationally vulnerable banded dotterel (Wildland Consultants Ltd., 2015).



Figure 5: Lake Rotokawa.

There are approximately 25 geothermal pools in the vicinity of Lake Rotokawa and collectively they occupy an area of 6.3 ha. The largest one, the Lake Rotokawa Geothermal Lagoon, which sits immediately adjacent to the lake and discharges its geothermal water directly into the lake, occupies 6,538 m^2 (Wildland Consultants Ltd., 2015).

Further details of the ecology and biodiversity aspects of Waikato geothermal lakes and pools can be found in Catlin et al. (2017) and Duggan and Boothroyd, (2022).

3. WAIKATO REGION'S GEOTHERMAL POOLS ELSEWHERE

There are 113.4 ha of geothermal water in the Waikato Region. The five largest geothermal lakes described above account for 83.3 ha, leaving 30.1 ha mostly scattered across 64 geothermal sites of surface geothermal activity (Wildland Consultants Ltd., 2015) in the region's 15 large geothermal systems (Figure 1).

This section discusses the twelve geothermal fields containing the largest surface area of geothermal water other than the lakes described above ((Wildland Consultants Ltd., 2015).

The region's thirty or so small geothermal systems also have small areas of geothermal water, but only one such pool, Taahunaa tapu Waiariki o Toa at Whangairorohea (600 m^2), is sizable. The remainder are less than 100 m^2 each.

3.1 Mt Tongariro

The biggest by far of the geothermal pools in large geothermal systems is the Sulphur Lagoon, in the Upper Te Maari Crater, on the northern slope of Mt Tongariro, in the Tongariro National Park. Te Maari is a hydrothermal system on the side of Mt Tongariro and is subject to occasional massive hydrothermal eruptions, which are at least partially

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fuelled by volcanic activity, with the most recent eruption occurring in 2012. Therefore, Sulphur Lagoon can be considered both a volcanic and a geothermal pool. The pool has an approximate area of 8,603 square metres. This is less than the 1.1 ha measured in a 2011 winter field survey when the lake was iced over (Wildland Consultants Ltd., 2015); however, the area can vary depending on the effects of hydrothermal eruptions and weather-related factors such as snow fall and snow melt. Due to its remote location, it is not often visited for monitoring purposes. The lagoon area may be reviewed using aerial photography and in particular the high-resolution imagery of the Waikato Region produced every five years by the Waikato Regional Council (WRAPS: Waikato Regional Aerial Photography Survey), which is publicly available through its website's data portal and other sources.

Also on Mt Tongariro are located the Emerald Lakes (Ngarotopounamu), three pools occupying hydrothermal eruption craters and heated by geothermal gases. They owe their striking colour to sulphur gases rising through the water. The lakes have a pH of 3 to 5. Together they comprise 0.9 ha. The largest pool is 4.3 m deep and overflows into the Oturere River. The lakes have a summer temperature of 13 °C (Michaelis, 1982).

3.2 Tokaanu

Tokaanu Geothermal Field, at the southern end of Lake Taupō, is part of the Tokaanu-Waihi-Hipaua Geothermal System. On the edge of the settlement of Tokaanu, the Tokaanu Thermal Park Recreation Reserve has many geothermal features including pools, sinter-forming springs, geysers, and hot streams. The geothermal water bodies including streams cover 0.2 ha in total (Wildland Consultants Ltd., 2015).

On the shore of Lake Taupō is a large geothermal wetland that includes ten areas of geothermal open water, which between them make up 4.6 ha (Wildland Consultants Ltd., 2015). Little is known about these areas of geothermal water as access through the wetland is difficult. Some of the wetland is on private land and some is part of the Tokaanu Recreation Reserve.

3.3 Orakei Korako

The Orakei Korako Geothermal System has four distinct and separate areas of geothermal activity lying along a stretch of land bordered to the west by the Waikato River and to the east by the Paeroa Range. The four areas are, from north to south, Waihunuhunu, Akatawera Stream, Orakei Korako, and Red Hills. Both Orakei Korako and Red Hills have a small proportion of their geothermal features on the west side of the river. Waihunuhunu has a geothermal wetland that accounts for most of the geothermal water at Orakei Korako, at 2.6 ha. It is in an arm of the Waikato River and is on unprotected private land. At Akatawera Stream, the only geothermal water is in the stream itself, which runs through private land (Wildland Consultants Ltd., 2015).

At Orakei Korako, most of the geothermal features are found within Orakei Korako Geothermal Park, a tourism site within the Whirinaki Stream Marginal Strip administered by the Department of Conservation. Most of the Orakei Korako geothermal features were drowned when the Waikato River was dammed for hydroelectricity development, creating Lake Ohakuri. What remains above water level is only about a quarter of what was visible previously. The largest geothermal pools at Orakei Korako Geothermal Park and Red Hills, although spectacular for their brilliant white sinter deposits and clear blue water, are no more than a few metres across; however, there are many of them occupying less than 0.1 ha at the Geothermal Park. At Red Hills, the main area of geothermal water, measuring approximately 0.2 ha, is a small area of open geothermal water on the margin of Lake Ohakuri (Wildland Consultants Ltd., 2015).

3.4 Waikite

Waikite Geothermal Field, like Waiotapu, is part of the Waikite-Waiotapu-Waimangu Geothermal System. It has a total of 0.8 ha of geothermal water, on Conservation land (Wildland Consultants Ltd., 2015). Its largest geothermal pool, Lake Puakohurea, is 3581 m^2 and is situated approximately two kilometres up the Waikite Valley, northeast of the thermal bathing complex, in a remote area known as Puakohurea Springs. Another pool, called Te Manaroa, accessed through the bathing complex, is quite small by comparison, having an area of approximately 44 m^2. However, it is said to have the greatest discharge rate of all geothermal springs in New Zealand. This discharge has a flow of 40-50 litres per second of near-boiling bicarbonate (HCO_3^-) water depositing bright white travertine on the pool surrounds and stream bed (Cody et al., 2021). A 9 ha geothermal wetland, just upstream of the bathing complex, has been restored by the Department of Conservation after a largely unsuccessful attempt to drain it. The natural water level has been re-established and the geothermal wetland habitat is recovering (Cashmore and Thompson, 2019).

3.5 Te Kopia

Te Kopia Geothermal System is on the Paeroa Fault scarp southwest of Waikite and northeast of Orakei Korako. At the base of the scarp there are several large geothermal pools, totalling 0.8 ha (Wildland Consultants Ltd., 2015). The largest of these is about 0.26 ha. Although the pools are on Conservation land, all but the northern ones are difficult to access as private land must be crossed to get to them.

3.6 Reporoa

The Reporoa Geothermal System borders the southern end of the Waiotapu Geothermal Field. It has three areas of geothermal activity within an area of mainly flat farmland to the east of the Paeroa Range: The Longview Road Geothermal Area, The Wharepapa Rd Geothermal Area and Golden Springs. The Longview Road Geothermal Area occupies the Molloy Conservation Area and has several large pools totalling 0.3 ha. The Wharepapa Rd Geothermal Area is on private land and has numerous geothermal pools of various sizes totalling 0.2 ha. Golden Springs geothermal features are on private land on both sides of State Highway 5 and include a warm pool and a stream (Wildland Consultants Ltd., 2015). Several kilometres away, Butcher's Pool, a public geothermal bathing pool with concrete and wooden surrounds belonging to Rotorua District Council, is about 6 metres by 8 metres. It is in a small grassy public reserve and has an adjacent picnic area and a toilet.

3.7 Wairakei-Tauhara

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The Wairakei-Tauhara Geothermal System occupies approximately 120 square kilometres and covers most of Taupō town and the surrounding rural area. The Wairakei Power Station, which is the second industrial-scale geothermal power station installed in the world after Larderello in Italy, and the first in New Zealand, is found here. The Wairakei-Tauhara Geothermal System currently supports four geothermal power stations, several direct-use geothermal industrial users, geothermal tourism and spa operators, and numerous accommodation providers offering geothermal spa facilities (Barns and Luketina, 2011). It has eighteen areas of geothermal surface activity but currently there are no more geothermal lakes and only 0.5 ha of geothermal water left. Much of this is in the several geothermal streams fed by springs (Wildland Consultants Ltd., 2015). The largest geothermal pool is Pirorirori, in the Waiora Lakes area. This pool is known by some as Alum Lake, and the Waiora Lakes area also known as Alum Lakes. Most of the numerous spectacular multi-hued lakes there dried up in the 1990s. Evidence points to the cause being the large-scale extraction of geothermal fluid, which previously had been responsible for the demise of most of the geothermal springs on the geothermal system (Newson and O'Sullivan, 2007). A likely mechanism for this is a hydrothermal eruption cracking the aquiclude underlying the lakes and allowing them to drain. Pirorirori was the slowest of the Waiora Lakes to drain. It originally had an area of 0.23 ha, but now is split into two lakes, the larger one being less than 700 square metres.

3.8 Mōkai

The Mōkai Geothermal System is northwest of the Wairakei-Tauhara Geothermal System and supports a geothermal power station and several direct uses of geothermal heat, including a 12-ha commercial greenhouse growing tomatoes and capsicums, and a milk-drying plant. Geothermal springs exist at Whakamaru lakeshore, Tirohanga Rd, Paerata Rd, and Waipapa Stream, all part of the Mōkai Geothermal System. There is less than 0.5 ha of geothermal water in total, mostly a series of geothermal pools occupying hydrothermal eruption craters at Tirohanga Rd, the largest of which is approximately 850 square metres. There are numerous smaller pools at Paerata Rd (Wildland Consultants Ltd., 2015).

3.9 Ngatamariki

The Ngatamariki Geothermal System is west of Ohaaki and has a power station on it: Ngatamariki power station. The system has two areas of geothermal surface features, at Orakonui Springs and at the Waikato River Springs. In total, the geothermal water there amounts to no more than 0.3 ha. Small areas of geothermal wetland and pools exist on both sides of the Waikato River: at Waikato River Springs and at Orakonui. There are numerous hot springs and pools in these areas; the largest of which covers 1,440 square metres (Wildland Consultants Ltd., 2015) and occupies a crater formed during a hydrothermal eruption in April 2005 (Cody, 2005).

3.10 Ohaaki

Ohaaki Geothermal System is north of Rotokawa and in the 1980s was New Zealand's second geothermal system to be developed for electricity generation, after the Wairakei Geothermal Power Station (Kortright, 2015). It has less than 0.1 ha of geothermal water, mainly found in the Ohaaki Ngāwhā (Wildland Consultants Ltd., 2015), a large geothermal pool occupying approximately 700 square metres, which before electricity development was famed for its deep blue clear water and its extensive sinter terracing surrounding it on all sides. The Ngāwhā Pool went dry during the early years of development and is now kept full by the input of bore water (Glover and Hunt, 1996). Because the outlet is channelled into a bath house, this does not allow the overflow that would constantly regenerate the sinter terrace and cover the existing weathered sinter. Three large discharge ponds associated with the power station and its borefield operations are bigger than the Ngāwhā, one being almost a hectare in area.

3.11 Horohoro

Horohoro Geothermal System is the northern-most large geothermal system in the Waikato Region. The only industrial use it has is a greenhouse operation. There is less than 0.1 ha of geothermal water (Wildland Consultants Ltd. 2015), as there are naturally few discharging geothermal features there. The largest pool, on Māori Trust land, is known as Waipupumahana and is used by the owners for bathing. It occupies one of several hydrothermal eruption craters in the area and is approximately 70 square metres in area.

3.12 Atiamuri

Atiamuri Geothermal System is northeast of Mōkai and southwest of Horohoro Geothermal System. It has two large and spectacular geothermal pools in the Whangapoa Springs Scientific Reserve, each about 50 square metres in area (Wildland Consultants Ltd., 2015).

4. INVERTEBRATE ECOLOGY OF THE WAIKATO REGION'S GEOTHERMAL LAKES AND POOLS.

In 2002 a study was undertaken on invertebrates within geothermal pools (Duggan and Boothroyd, 2022) with the following outcomes:

- Description of the phytoplankton, zooplankton and macroinvertebrate communities in a variety of standing water geothermal habitats;
- Measurements of invertebrate community changes along geothermal stress gradients, and;
- Examination of the significant habitat and environmental factors influencing the diversity and distribution of aquatic geothermal invertebrate communities.

The following is largely taken from verbatim from the report's executive summary:

Samples were collected from waterbodies in five geothermal fields within the TVZ: Waiotapu, Orakei Korako, Golden Springs, Rotokawa and Waikite. Additional samples were collected from two non-geothermal waterbodies, Lakes Ngapouri and Ngahewa, to provide a comparison with geothermal sites. The diversity of biota was typically low in the geothermally influenced waters compared with non-geothermally influenced waters. Biota were found to respond to gradients in environmental and habitat conditions within and between geothermal fields.

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The phytoplankton of geothermal waters was dominated by diatoms or cyanobacteria. The spatial distributions of dominant algal groups in relation to physicochemical conditions appeared to be generally consistent with patterns observed in flowing water geothermal habitats. Water temperature and chemical composition (e.g., pH and sulphide concentrations) were generally important in determining distribution, with cyanobacteria dominating at higher temperatures but not in highly acidic waters. However, some cyanobacteria populations were found in some highly acidic, high sulphide sites in the Waiotapu and Rotokawa fields. Algal biomass (chlorophyll *a*) was typically low at these sites.

Zooplankton were most commonly represented in geothermal waters by rotifers, cyclopoid copepods, and early instar chironomids. Monogonont rotifers were uncommon but represented by *Lecane* species in two water-bodies, and *Synchaeta pectinata* in another. *Bdelloid* rotifers were ubiquitous in their distribution in the geothermal sites. The cyclopoid copepod *Paracyclops waiariki* was recorded from several ponds in the Waiotapu geothermal field and appears to occur obligately in geothermal waters. *Eucyclops serrulatus* was recorded in warmer sites (up to 32.2 °C) with circum-neutral pH. Differences in zooplankton composition were observed between the geothermal sites, with high temperature and acidity, compared to sites that had no geothermal influence.

Macroinvertebrates recorded in this survey were typical of those that had been recorded in geothermally influenced sites previously. Taxa richness declined with increasing temperature and acidity. The degree of acidity of each waterbody was also the dominant factor determining the community composition and abundance of macroinvertebrate species within geothermal fields and between sampling locations. Acidic sites were distinguished by having high relative abundances of *Neoscatella sp., Culex rotoruae, Liodessus deflexus, Anisops wakefieldi* and *Chironomus zealandicus.* The more alkaline lakes were also separated along a temperature gradient. Warmer, alkaline sites from Lake Ohakuri and Waikite were dominated by *Enochrus tritus, Chironomus* sp. *a* and *Paratrichocladius pluriserialis.* Annelids, *Paroxyethira hendersoni* and *Pisidium* were found to be more typical of non-geothermally influenced sites. Chlorophyll *a* and dissolved oxygen concentrations also appeared to be important in determining the distribution of macroinvertebrate species.

Overall, the fauna of geothermal sites comprised mainly thermo-tolerant or acid-tolerant species. However, several zooplankton and macroinvertebrate taxa were obligately restricted to or recorded most commonly from geothermal waters, and many taxa, particularly zooplankton, were recorded from a limited number of water bodies and in extremely low numbers. The combination of restricted distribution and low density is likely to make the geothermal fauna more vulnerable to extinction if significant changes were to occur in the geothermal resources. (Duggan and Boothroyd, 2022).

5. MICROBIAL ECOLOGY OF THE WAIKATO REGION'S GEOTHERMAL LAKES AND POOLS.

The 1000 Springs project, a collaboration between GNS Science several New Zealand universities in 2017, measured bacterial and archaeal community composition, 46 physicochemical parameters, and metadata from 925 geothermal springs, lakes and pools across New Zealand (13.9–100.6 °C and pH < 1–9.7) (Power et al., 2018).

It determined that diversity is primarily influenced by pH at temperatures <70 °C; with temperature only having a significant effect for values >70 °C. Further, community dissimilarity increases with geographic distance, with niche selection driving assembly at a localised scale. Surprisingly, two genera (Venenivibrio and Acidithiobacillus) dominated in both average relative abundance (11.2% and 11.1%, respectively) and prevalence (74.2% and 62.9%, respectively). A total of 28,381 operational taxonomic units were detected. These findings provide an unprecedented insight into ecological behaviour in geothermal springs, and a foundation to improve the characterisation of microbial biogeographical processes (Power et al., 2018).

6. PROTECTING GEOTHERMAL LAKES AND POOLS FROM ADVERSE EFFECTS

Geothermal surface features are rare and delicate, and New Zealand has already lost many of them from three main causes:

- Hydroelectric lakes: All the Waikato Region's large geothermal systems are close to the Waikato River, and geothermal features at Orakei Korako and Mangakino have been drowned by the creation of the hydroelectric lakes Ohakuri and Maraetai respectively.
- Geothermal electricity developments: These extract large volumes of geothermal fluid from depth, reducing subsurface pressure, which in turn results in a reduction or loss of flow of geothermal water to surface features, and an increase in steam production. At Wairakei and Ohaaki, these effects have led to the extinction of sinter-depositing springs, geysers, lakes and pools, while the area of heated ground has increased.
- hydrothermal eruptions: Another effect can be an increase in the frequency and intensity of hydrothermal eruptions and micro-earthquakes, which can move faults, crack aquicludes and have other effects on the local hydrology that lead to draining of lakes and pools.

Surface activities that can adversely affect geothermal lakes and pools include draining them for other uses. For instance, one of the Whangapoa pools at Atiamuri had one-metre-deep channel dug from it to feed a public bathing pool. The other poolō was partially drained for forestry purposes, but this has since been rectified. (Cody et al., 2021).

Waikato Regional Council policies and rules protect geothermal lakes and pools from adverse effects of land uses and uses of geothermal resources (Waikato Regional Council, 2011, 2016).

8. CONCLUSION

Geothermal lakes are rare on Earth. New Zealand's geothermal lakes are confined to those parts of the Waikato and Bay of Plenty Regions that the Taupō Volcanic Zone occupies. Geothermal water bodies, including geothermal lakes, are defined by their geochemistry and geomorphology, which can be clearly differentiated from that of volcanic or freshwater lakes. There are five geothermal lakes in the

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Waikato Region, four of them occupying hydrothermal eruption craters. The fifth, Lake Orotu, is a peat lake with geothermal inputs and is the only one that supports vertebrate aquatic fauna. Nevertheless, all geothermal lakes provide extremophilic habitat and have a rich microbial diversity.

In addition to the geothermal lakes, there are hundreds of geothermal lakelets, pools, and lagoons in the Waikato Region, most of them are smaller than 0.1 ha. Like all geothermal surface features, geothermal lakes and pools are vulnerable to extractive uses of geothermal fluid and energy and to land uses.

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Table 1 Characteristics and Water Quality of the Waikato's largest geothermal lakes.

Attribute	Unit	Rotowhero (surface)	Rotowhero (bottom)	Whangioterangi (surface)	Whangioterangi (bottom)	Ngakoro	Orotu (peat) [a]	Orotu (geothermal)	Rotokawa
Area	ha	2.6[a]		3.6[a]		7.0 [a]	4.7 [a]		65.4 [a]
Depth	m	18.4[b]		32 [b]			0. 8[b]		27[f]
Temperature [a]	**°C**	31.5 [a]		22 [b]		25[d]	21.4 [b]		23.1[f]
pH		3.2 [b]		2.8 [b]		2.8 [b]		3.0 [b]	2.3 [b]
Sodium **Na^+**	g m^{-3}	158 [b]		180 [b]		701 [b]			225 [b]
Potassium **K^+**	g m^{-3}	29.0 [b]		50.0 [b]		84.8 [b]			25.0 [b]
Calcium **Ca^{2+}**	g m^{-3}	16.0 [b]		20.0 [b]		23.0 [b]			15 [b]
Magnesium **Mg^{2+}**	g m^{-3}	2.2 [b]		3.0 [b]		1.8 [b]			3.0 [b]
Turbidity [a]	NTU	3.6	3.1	34	51		5	5.1	
Volatile suspended solids [a]	g m^{-3}	6	5	4	6		6	9	
Total suspended solids [a]	g m^{-3}	6	5	4	6		10	9	
Ammonium [a]	g m^{-3}	1	1	11.1	11		4.9	5.3	210 [c]
Nitrate [a]	g m^{-3}	<0.002	0.003	<0.002	<0.002		0.015	0.032	16 [c]
Total Kjeldahl nitrogen [a]	g m^{-3}	1.59	1.57	11.4	11.5		6	5.6	

a (Catlin et al., 2017)
b (Timperley and Vigor-Brown, 1986)
c (Forsyth, 1977)
d (Lloyd, 1959)
e (Mann et al., 1986)

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Table 2: Major ion concentrations (g m^3) in waters contributing dissolved salts to lakes. Reproduced from Timperley and Vigor-Brown (1986)

Lake Type	pH	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	HCO_3^-
Geothermal water	8.3	1330	198	23.0	0.18	2290	35.0	66.0
Geothermal steam	3.3 – 23	0	0	0	0	0	148 – 1003*	0
Cold spring water (rhyolite pumice)	7.2	9.6	1.4	3.0	1.4	2.9	2.4	40.8
Cold spring water (welded ignimbrite)	6.8	8.0	12.7	2.3	1.3	5.2	2.4	27.0
Stream water (rhyolite pumice)	6.8	5.1	1.3	2.9	1.0	2.6	1.7	23.1
Precipitation	5.2	0.58	0.21	0.14	0.084	1.2	0.55	0.0

*g t^{-1}

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