The Rotokawa-Mokoia Geothermal System - science, monitoring and use summary report

Bay of Plenty Regional Council
Environmental Publication 2024/01

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ISSN: 1175-9372 (Print)
ISSN: 1179-9471 (Online)

Acknowledgements

Ngā mihi Breda Savoldelli, Laura Boucher and Penny Doorman, Bay of Plenty Regional Council (BOPRC) for reviewing the report and adding your 'lens' to it as per your key areas of expertise (groundwater, comms and cross-council aspects, respectively). Nga mihi Shane Iremonger (BOPRC) for final science peer-reviewing of the report. Thank you John Burnell (GNS Science) for reviewing the geothermal-groundwater use spreadsheet and providing advice to improve recordkeeping. Finally, ngā mihi Jacqui Kaai (BOPRC) for formatting this report and doing the graphs work for the cover.

Executive summary

The Rotokawa-Mokoia Geothermal System (RMGS) is located east of Lake Rotorua. The system is classified as Group 3 (conditional development) under the Bay of Plenty Regional Natural Resources Plan (RNRP) and the Regional Policy Statement (RPS), where extraction of geothermal water, heat and energy is provided for where significant adverse effects on Significant Geothermal Features are avoided, remedied or mitigated.

The geothermal system extends from Mokoia Island to northwest through to Rotokawa to southeast, including the Rotorua Airport area and the bottom of Lake Rotorua between the Island and the Airport. The main thermal areas are around the southeast shore of the Island and around Rotokawa. The geothermal surface features in both areas are fed by the same source aquifer at depth. Some level of shallow hydrological connection between the Rotokawa-Mokoia and the Rotorua City systems may exist throughout a ‘neck’ along the bed of southeast Lake Rotorua, as well as deep connection many kilometres deep, at heat source level.

The RMGS is relatively small compared to other high-temperature systems of the Taupō Volcanic Zone (TVZ); ~11 km^2 surface area compared to ~18-29 km^2 of the Rotorua City system. Subsurface temperatures are relatively high at shallow depths in some areas, but significantly below the temperatures encountered in the Rotorua City system. Nonetheless, it suits the temperature requirements for the current extractive uses at the RMGS (light space and water heating, cooking and bathing in mineral pools).

There is currently a reasonable level of scientific knowledge around the extent and nature of the RMGS. However, this knowledge is not captured in the conceptual model currently available for the RMGS. This is because the model was developed in the early 1980s, prior to most key geoscientific surveys in the area. This knowledge is thus yet to be translated into an updated, robust conceptual model for the system. The development of an updated conceptual model will be key to inform the management of the system, including any future use direction and environmental monitoring programme.

Currently, geothermal environmental monitoring and consents monitoring is limited. From the data available, it is not possible to determine the state and trends of the RMGS, neither correlate changes in state with changes in use, if present. Improved monitoring would help to overcome those issues, and is a matter that is being considered by BOPRC.

Current levels of use of geothermal water and energy is very low: ~81 tonnes per day (water gross take) and ~6.4 megawatts-hour (thermal) per day (heat net take). Based on the data currently available, the RMGS is likely a small geothermal system. Therefore, it is difficult to determine what this low level of use means to the health of the geothermal system and its surface features. An assessment of the size of the resource would help to understand opportunities for sustainably use, while protecting the significant geothermal surface features.

About 60% of the geothermal water extracted from the shallow geothermal aquifer via production wells is currently discharged to waste (net mass loss). Opportunities for increased support of the health of the geothermal aquifer through reinjection could be explored.

Contents

Scope and purpose of the report

The Bay of Plenty Regional Policy Statement (RPS) identifies 16 geothermal systems in the Bay of Plenty region, including the Rotokawa-Mokoia Geothermal System (RMGS). The Plan Change 11 (PC11) of the Regional Natural Resources Plan (RNRP) is currently being progressed with a draft for consultation currently in development.

The RMGS is currently classified as Group 3 (conditional development) under the RNRP and the RPS. Other systems in this category include Tikitere and Tāheke, approximately 4 km and 9 km to northeast of the RMGS, respectively.

Under the policy framework for Group 3 systems, the extraction of geothermal water, heat and energy is provided for where significant adverse effects on Significant Geothermal Features are avoided, remedied or mitigated.

As part of the plan change process, it will be important for engagement purposes to provide the community with more information on the Rotokawa-Mokoia Geothermal System. This report was developed to provide the community with a summary of all the scientific information on the system, environmental monitoring and the current level and types of use and discharges. Based on the information presented, it also outlines key knowledge and gaps and potential work that could be done to fulfil those gaps.

- Part 1 of this report summarises the geoscientific information on this system. This includes information on:
  - The conceptual model of the RMGS.
  - Geothermal surface features.
  - Geology and geological controls on fluid flow.
  - Geophysics.
  - Geochemistry and geothermometry.
  - The Rotokawa-Mokoia Geothermal System extent and its potential hydrological connection with the Rotorua City Geothermal System.
- Part 2 provides detailed information on the use of geothermal water and energy from the system, as well as selected relevant information on the use of groundwater.
- Part 3 of the report presents a summary of the report, the identified key scientific and monitoring gaps relevant to BOPRC functions as resource managers and potential future work to fulfil those gaps.

This is a factual report of technical/scientific nature. An assessment of options for future management, values and policies is beyond the scope of this report. Mātauranga Māori is also outside the scope of this report.

Part 1:
Science and monitoring

1 Introduction

The Rotokawa-Mokoia Geothermal System, like the Rotorua City system, is a by-product of the volcanism associated with the evolution of the Rotorua Caldera of the Taupō Volcanic Zone (TVZ). The TVZ is the result of the oblique subduction of the Pacific plate beneath the Australian plate at the Hikurangi Subduction Margin located off the east coast of Aotearoa New Zealand (Reyners, 2013; Milner, 2001).

Volcanism at the Rotorua Caldera begun circa 240 thousand years ago (ka) with a major single-event eruption. This event generated an impressive ~200 km^3 of volcanic deposits (the Mamaku ignimbrite), which is extensively exposed around the Mamaku Plateau (Milner, 2001). This large volume of erupted material reflects the magnitude and importance of this volcanic event to the geological evolution of the Lake Rotorua area. Several small rhyolitic lava domes erupted following this major explosive eruption, including the Mokoia Island lava dome about 158 ka ago and the Ngongotahā-Pukehangi dome complex, two of the most prominent landforms around Lake Rotorua (Figure 1; Milner, 2001, Leonard *et. al.*, 2010; Bertrand *et. al.*, 2022).

The last eruption at the Rotorua Caldera is estimated to be older than 20,000 years (Leonard *et. al.*, 2010). Chances of new eruptions are considered very low. Small earthquake swarms occur approximately every two to ten years, but none of these events are of large magnitude nor are they associated with volcanic unrest (Milner, 2001; Gravley *et. al.*, 2007, Kaye, 2008).

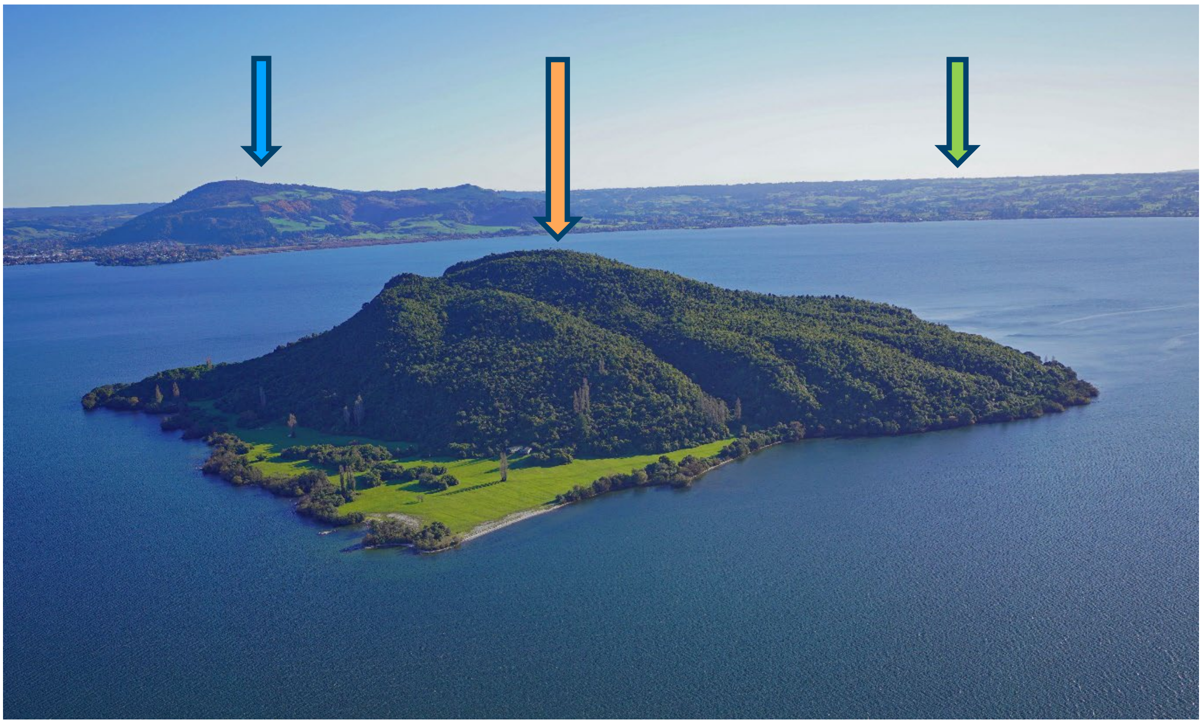

Figure 1: Ngongotahā-Pukehangi and Mokoia domes (blue and orange arrows, respectively), two post-caldera rhyolite lava domes associated with the evolution of the Rotorua Caldera. Mamaku Plateau/Ignimbrite in the background (green arrow). Image from Photoblique (https://photoblique.com/).

2 The Rotokawa-Mokoia Geothermal System

The Rotokawa-Mokoia Geothermal System is located on the eastern side of Lake Rotorua, around 8 km northeast of Rotorua City. It consists of a high-temperature system extending from the eastern shores of Mokoia Island in the west-northwest, through to Lake Rotokawa in the east-southeast. A potential zone of shallow hydrological connection with the Rotorua City Geothermal System may exist through a ‘neck’ along the southeast Lake Rotorua bed as well as a deep connection many kilometres deep, at heat source level (Section 2.6).

The RMGS is a relatively small system, with a surface extent of about 11 km^2. This compares with ~18-29 km^2 for the Rotorua City system. Subsurface temperatures are relatively high, reaching up to 120°C at less than 100 m depth in Rotokawa. The geothermal aquifer is anticipated to be hotter at greater depths (to at least 500m depth), possibly in the mid-upper 200°C range. Geothermal activity, such as hot springs, is limited mainly to the southeast shore of Mokoia Island and Rotokawa (*Figure* 2),and some small warm seeps around the lake shore within the Rotorua Airport area (Figure 4).

Figure 2: The two key areas of surface expression of the RMGS inland: around the geothermally influenced lakelet, Lake Rotokawa (orange arrow) and around the Ngunguru Point (green arrow; cf. Figure 7). Image from Photoblique (https://photoblique.com/).

Chemistry data and the wider geological-geothermal context indicates that the surface features at Mokoia Island and onshore at Rotokawa are fed by the same geothermal aquifer at depth (Section 2.1). Thermal springs at Mokoia Island are hotter than at Rotokawa, with temperatures up to 61°C in the Island compared to 40-45°C in Rotokawa. In both areas, the chemistry of the water has a typical composition for primary geothermal springs of the TVZ (alkali-chloride geothermal water diluted by groundwater).

The usual way to present all the geoscientific physical attributes of a geothermal system in an integrated way is through a conceptual model. This allows not only to present the data but also the understanding of the physical processes in play for the system. An acceptable model is not available for the RMGS (Section 2.1). This is because the only model currently available by Drolia *et. al.* (1981) was developed prior to the key geoscientific surveys that changed the understanding of this system. Nonetheless, there is now a significant body of information available to develop an updated model that matches the current understanding of the system. This information is summarised and presented in sections 2.2 to 2.5 below.

2.1 Conceptual model

A conceptual model of a geothermal system is a representation of the key attributes and understanding of the physical processes in play for a geothermal system. The conceptual model is typically presented as annotated maps and cross-sections, supported by a technical report containing the data and its analysis. Typically, a conceptual model portrays the following key information of a geothermal system:

- Key geological units and structures (e.g., faults).
- Thermal structure: isotherms and selected clay mineralogy.
- Hydrogeological units (e.g., geothermal aquifers and reservoir) and its connection with the geothermal surface features.
- Geothermal fluid thermodynamic state (e.g., boiling/two-phase, liquid, steam/gas).
- Fluid flow pathways.
- Water geochemistry and key chemical processes (e.g. boiling, dilution).
- Interactions/relationships with groundwater.
- Heat source: location and depth.
- Spatial extent in two and three dimensions, when possible.

A conceptual model is not merely a factual representation of data; it involves interpretation and integration of highly complex datasets by expert geothermal scientists and professionals. As a rule-of-thumb, the more quality data available, and the greater the expertise of those involved in analysing the datasets, the higher the likelihood that the conceptual model is robust (i.e. a realistic and accurate representation of the geothermal system). Conceptual models are not static either; they evolve over time as more or higher quality/detailed information becomes available.

The key datasets used to inform the development of conceptual models fall in the geoscience areas of geothermal geology, geophysics and geochemistry. Those geoscientific datasets are collected by surveying the surface and subsurface through various methods and, in the case of the Rotokawa-Mokoia Geothermal System, the bottom of Lake Rotorua. Conceptual models often improve significantly when/if production data (geothermal water/energy) becomes available, especially if production is large enough to perturb the current state of the system.

Sophisticated numerical models of a geothermal system can also be developed, but it requires quality data to input into the model to output quality results. Nonetheless, numerical models are also typically subjected to some level of uncertainty, depending on various factors.

Numerical modelling can also be used to test the conceptual hydrogeological understanding of the system against the complex thermodynamics and physics laws of fluid flow and chemistry. This helps to determine whether the conceptual model is essentially supported by physics. If not, the conceptual model likely needs to be refined and the model updated. The process of refining the conceptual and numerical models is an iterative one.

The RMGS currently does not have a widely-accepted conceptual model. The only model for this system was developed in the early 1980s, prior to various surveys of the 1990s-2000s that significantly refined and changed our understanding of the geothermal system. This model was developed by Drolia *et. al.* (1981) and only covers the Rotokawa area.

The conceptual model of Drolia *et. al.* (1981) infers that the upflow of the system is just north-east of Lake Rotokawa. This upflow zone would be where the deeper thermal waters ascend from depth to then be stored as an aquifer in the Rotoiti Breccia. Geothermal water interacts with cold groundwater at this level. This geothermal aquifer would be the source of water for warm/hot springs and production wells. The upflow is inferred to be structurally controlled by the intersection zone of west-northwest and north-northeast-trending fracture zones.

The two main consequences of the limited scope of Drolia *et. al.* (1981) model are that:

1. The model does not acknowledge and represent the likely interconnection between the Rotokawa and Mokoia Island thermal areas (i.e. that Rotokawa and Mokoia Island is one single geothermal system).
2. The potential hydrological connection between the RMGS and the Rotorua City Geothermal System is also not considered (cf. Figure 3 and Figure 4), neither their shared heat source.

More detailed information on the key geoscientific datasets currently available for the Rotokawa-Mokoia Geothermal System is presented in subsections 2.2 to 2.5. This data/information could be used in the future to update the conceptual model for the system.

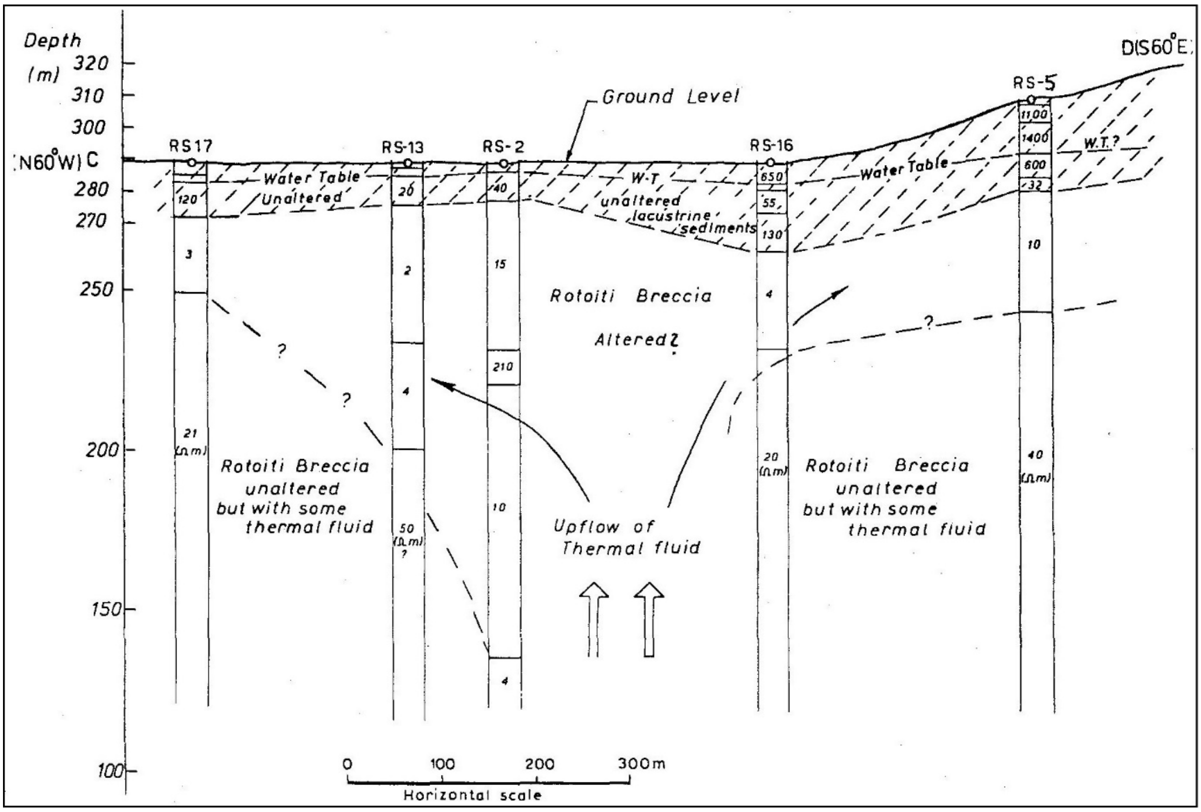

Figure 3: Conceptual model of Drolia et. al. *(1981). Note that this model is not currently considered a reasonable representation of the geothermal system, but a more updated model has not been developed and/or published to date.*

2.2 Geothermal surface features

Geothermal surface features are the surface expression of the wider geothermal system at depth and its aquifers. The surface features of the RMGS occur in three relatively small areas (Figure 5 to Figure 8):

- Along the south-eastern shores of Mokoia Island (hot springs).
- Around Lake Rotokawa (heated ground and warm seeps, including the geothermally influenced Lake Rotokawa).
- Around Ngunguru Point to the west of the Rotorua Airport, by the Lake Rotorua shore (warm seeps).
- Potentially at the bottom of Lake Rotorua, between the Island and the airport. This is inferred to consist of warm/hot water seeps and gas vents. This is based on the existence of high/moderate heat flow coinciding with the presence of pockmarks (de Ronde *et. al.*, 2023).

Some warm springs also occur on Hinemoa Point by Lake Rotorua's shore (not to be confused with Hinemoa Pool on Mokoia Island). These warm springs are in an area of potential hydrological connection with the Rotorua City system at depth (Figure 4; Section 2.6).

Hot springs on Mokoia Island are much hotter than the ones inland. Springs in the Island are up to 61°C (Bromley *et. al.,* 2006), while the surface features around Rotokawa and the airport are in the 40-45°C range (Drolia *et. al.*, 1981).

Lake Rotokawa is a prominent natural feature, classified as a cold, geothermally influenced lakelet. While Lake Rotokawa is cold (~12˚C) its geothermal influence is clearly marked by its low pH / high acidity (pH ~3) likely caused by the interaction between geothermal gases (mostly H_2S) with groundwater, and by its reasonably high sulphate content (~220 mg/L). CO_2 gas likely of geothermal origin is also reported to discharge vigorously in the eastern side of the lake (Figure 9).

Thermal activity may have been more extensive in the geological past (Drolia *et. al.,* 1981). This is evidenced by:

- Shallow clay alteration (≤ 5 m deep) about 200 m east of Lake Rotokawa, which is now a cool area.
- Presence of silica sinter and highly silicified tuffs around Ngunguru Point, but no geothermal feature actively discharging high-temperature/high-silica geothermal water.

Observations by local residents indicate a temperature decline for some springs in Rotokawa. Those reported changes are notably at ‘human time-scale’, and could be related to a potential natural waning state of this system or natural variability of the geothermal features. Currently it is not possible to verify, analyse and explain reported changes due to the limited environmental monitoring and use data (cf. Section 3).

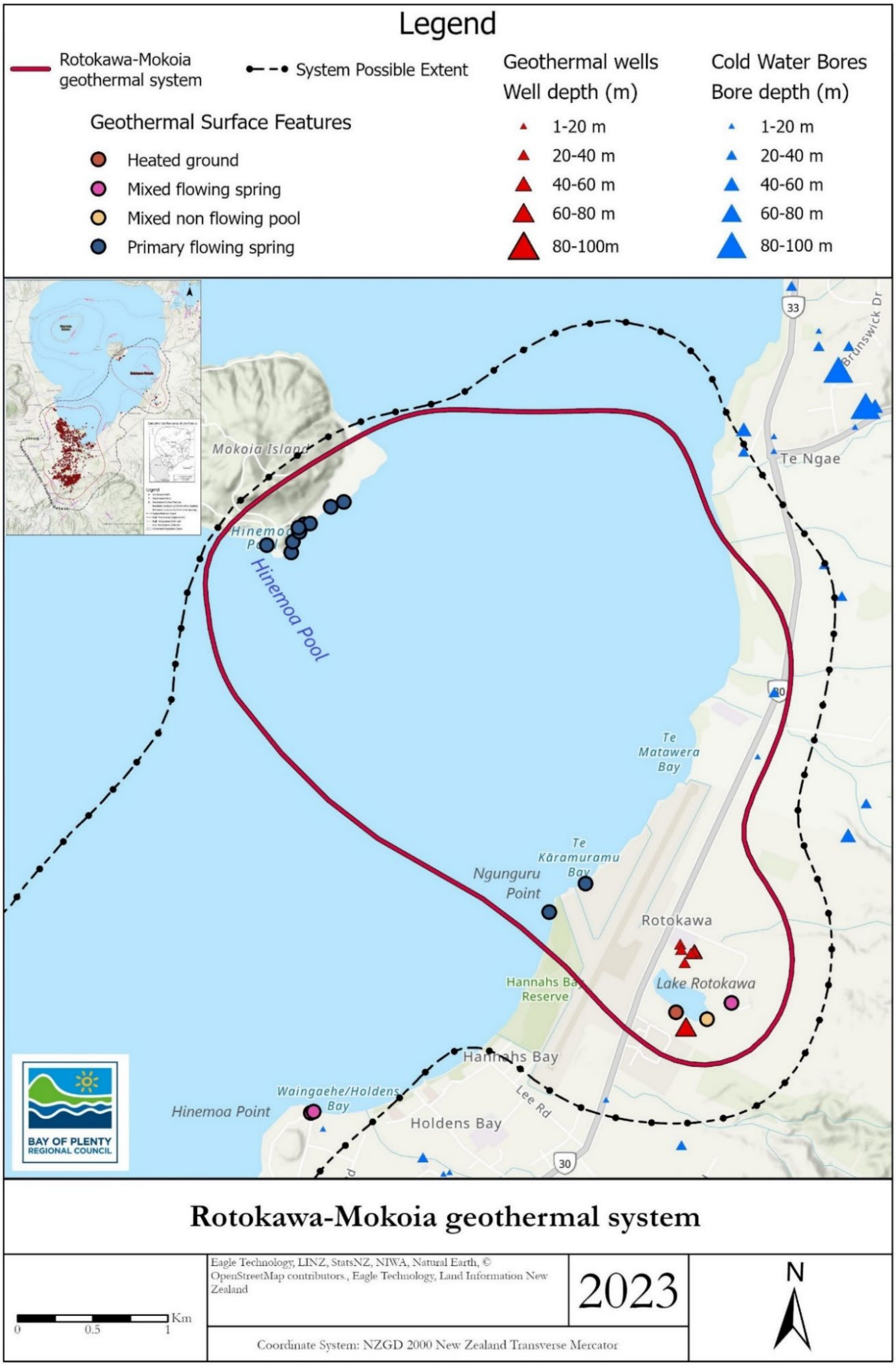

Figure 4: Rotokawa-Mokoia Geothermal System extent and a potential zone of hydrological connection with the Rotorua Geothermal System. Location and type of the geothermal surface features (dots). Location and depth category of the geothermal and cold wells (triangles). Surface feature data from GNS Science Geothermal Groundwater database (filtered).

Figure 5: Aerial (left) and Thermal Infrared (TIR) (right) images of southeast Mokoia Island. Red dots (left) are approximate locations of thermal springs – Hinemoa Pool is shown for reference (blue ellipse). Yellowish areas with a plume shape (right; one example as shown in the orange ellipse) are potentially natural geothermal discharges from surface features, but can also be related to groundwater seeps, anthropogenic discharges, weeds and/or other (Reeves, et. al.*, 2014).*

Figure 6: Aerial (left) and Thermal Infrared (TIR) (right) images of Rotokawa area. Yellow and light green dots (left) are approximate location of thermal features. Only the geothermally influenced Lake Rotokawa, the dominant feature of the photo, and one yellowish areas (red ellipse to the right) can be correlated to a mapped geothermal surface features (cf. Figure 4), however, the built environment and the small expression of the geothermal surface features (small size and relatively low temperatures) makes it difficult to readily identify the thermal areas for Rotokawa on TIR imagery, possibly due to insufficient resolution (< 5 m; Reeves et. al., 2014). Note: the grey ellipse on the image to the right is the discharge point of a consent and not a natural geothermal plume.

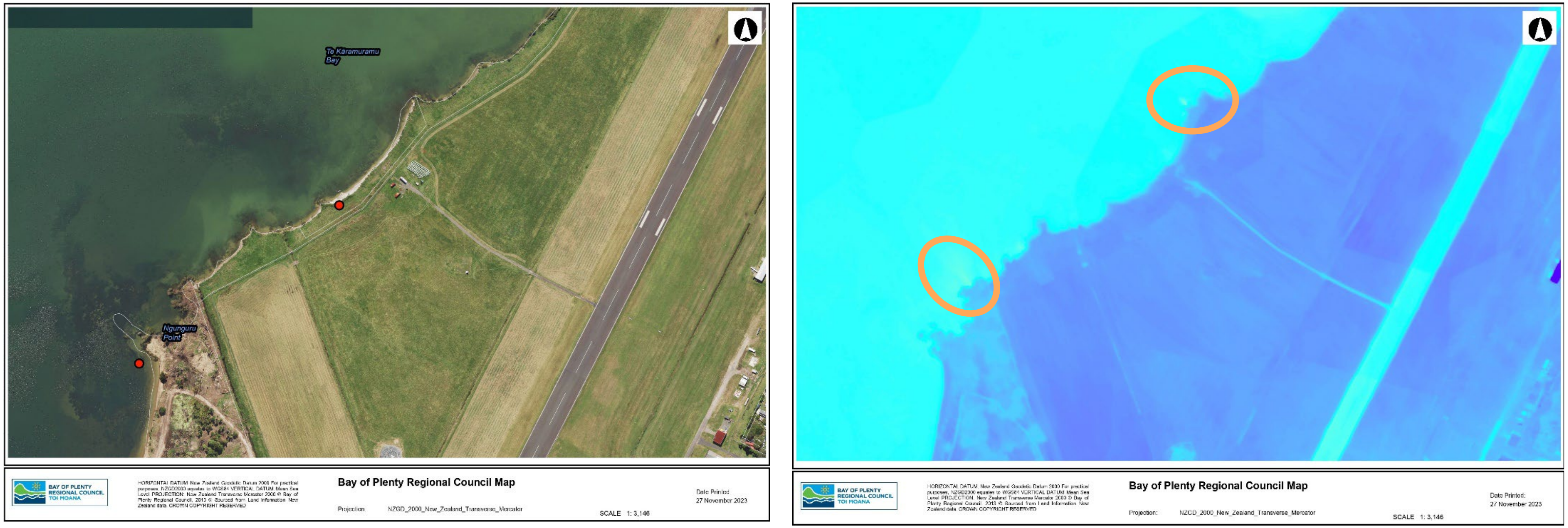

Figure 7: Aerial (left) and Thermal Infrared (TIR) (right) images of Ngunguru Point. Red dots (left) are approximate location of thermal features. Some of the yellowish areas (right; orange ellipses) are likely natural geothermal discharges from surface features, however, other yellowish areas are likely just shallow waters warmed by processes unrelated to geothermal activity like groundwater seeps and weeds.

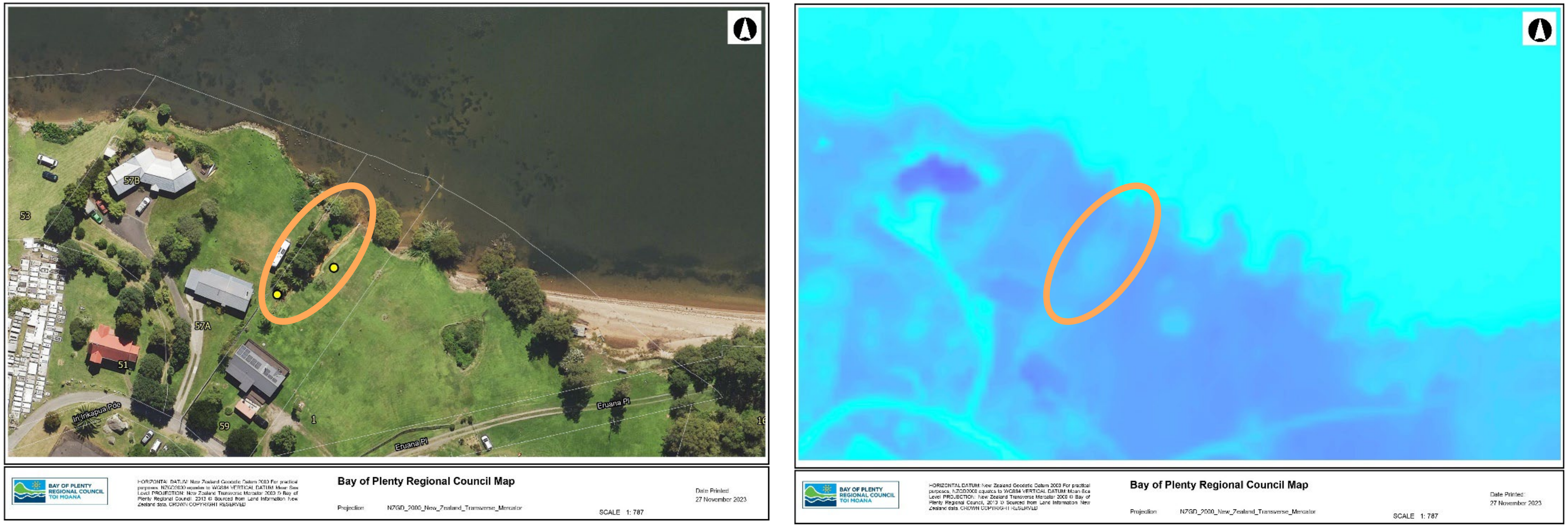

Figure 8: Aerial (left) and Thermal Infrared (TIR) (right) images of Hinemoa Point showing an 'orangey' water/deposit along a dug-in trench (orange ellipse). There are no yellowish areas indicating likely natural geothermal discharges from surface features, as with Figure 5 to Figure 7. However, the spring located along the trench has been historically recorded as warm and the 'orangey' nature of the water is indicative of some geothermal influence.

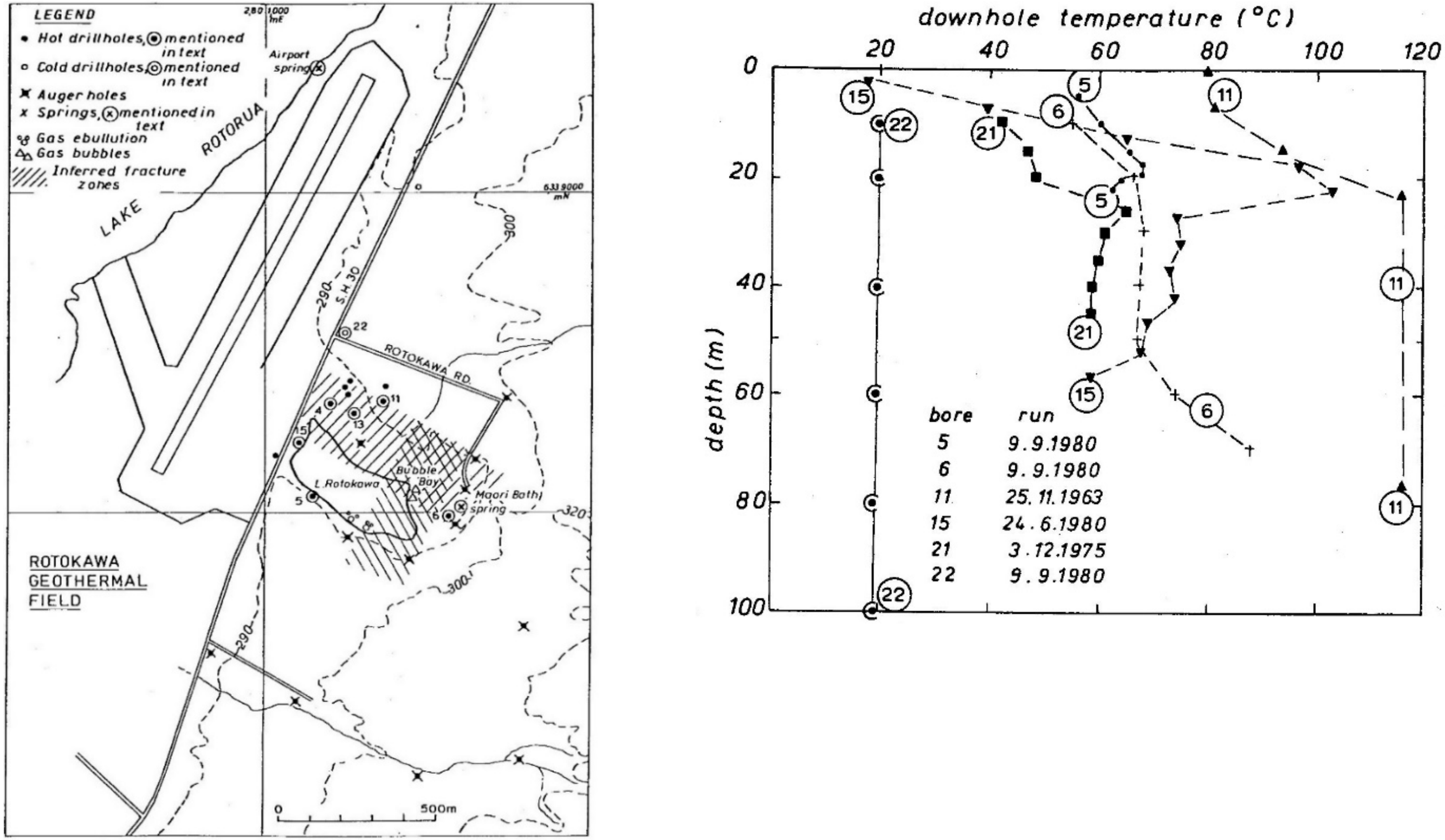

Figure 9: Map showing the key geographical sites in Rotokawa and the location of the wells and springs mentioned in the report (left). Compilation of downhole profiles. Note that Well 11 of Drolia et. al. (1981) is likely the same as LR904 on BOPRC database (right). After Drolia et. al. (1981).

2.3 Geology and geological controls on fluid flow

Geological surveys are used to understand the following key aspects of the geothermal system and/or a project area:

(a) Determine the geological units at depth and their characteristics (e.g. mineralogy).

(b) Establish the relationship between geological formations and hydrogeological units (hot and cold aquifers, reservoir, clay cap) and determine the geological controls on fluid flow (lithological and/or structural).

(c) Understand the past and present thermal structure and chemistry of the geothermal fluids, based on the mineral assembly and their textures.

(d) Validate other datasets, geophysics in particular.

(e) Map the thermal areas.

The geological context of the Rotokawa-Mokoia area is described by Leonard *et. al.* (2010), with a focus on the evolution of the larger Rotorua Caldera feature. At a local scale are the studies of Drolia *et. al.* (1981) and references therein, and Bibby *et. al.* (1992). Those studies are the key source of information on the geothermal geology and hydrogeology of the RMGS. The key aspects and findings of those reports are summarised below:

- A top unit composed of lacustrine sediments associated with Lake Rotorua water level changes over geological time scale (tens to hundreds thousand years). This unit might provide a geological seal/cap to the underlying geothermal aquifer.
    - Up to 30 m thick (but potentially 85 m thick in places, according to geological logs held by BOPRC).
    - Locally interbedded with fine layers of volcanoclastic sediments.
    - Generally unaltered other than localised kaolinitic (acid) alteration.
- A bottom unit composed of Rotoiti Breccia (ignimbrite) underlying the Lacustrine sediments. This unit may provide a lithological control to the geothermal aquifer, but this is unclear.
- The Mokoia Rhyolite lava dome, which dominates the landform of Mokoia Island. This lava dome is inferred to dip beneath the Lake for about 1 km laterally.
- Mixing of geothermal fluids with groundwater at shallow depths (first few hundreds of meters).
- Fluid flow westward at shallow depths (top few tens or hundred metres) towards Lake Rotorua, following the regional groundwater flow (Figure 10).
- An absence of major faulting within the area; however, second order, localised, concealed faults/fracture zones are possible (see below).
- An inferred narrow upflow zone (< 300 m) with a conical shape, centred north-east of Lake Rotokawa and controlled by the intersection of the WNW- with NNE-trending fracture zones. Springs in Rotokawa may be located and controlled by this fracture intersection zone.
- Thermal features on Mokoia Island controlled by the contact between the sedimentary units and the Mokoia Rhyolite, indicating they are likely controlled by enhanced permeability at the lithological interface.

Seward *et. al.* (2019) also infers that the connection between the onshore and the Mokoia Island areas of the geothermal system is structurally controlled by a WNW-ESE-oriented (west-northwest – east-southeast) fracture zone.

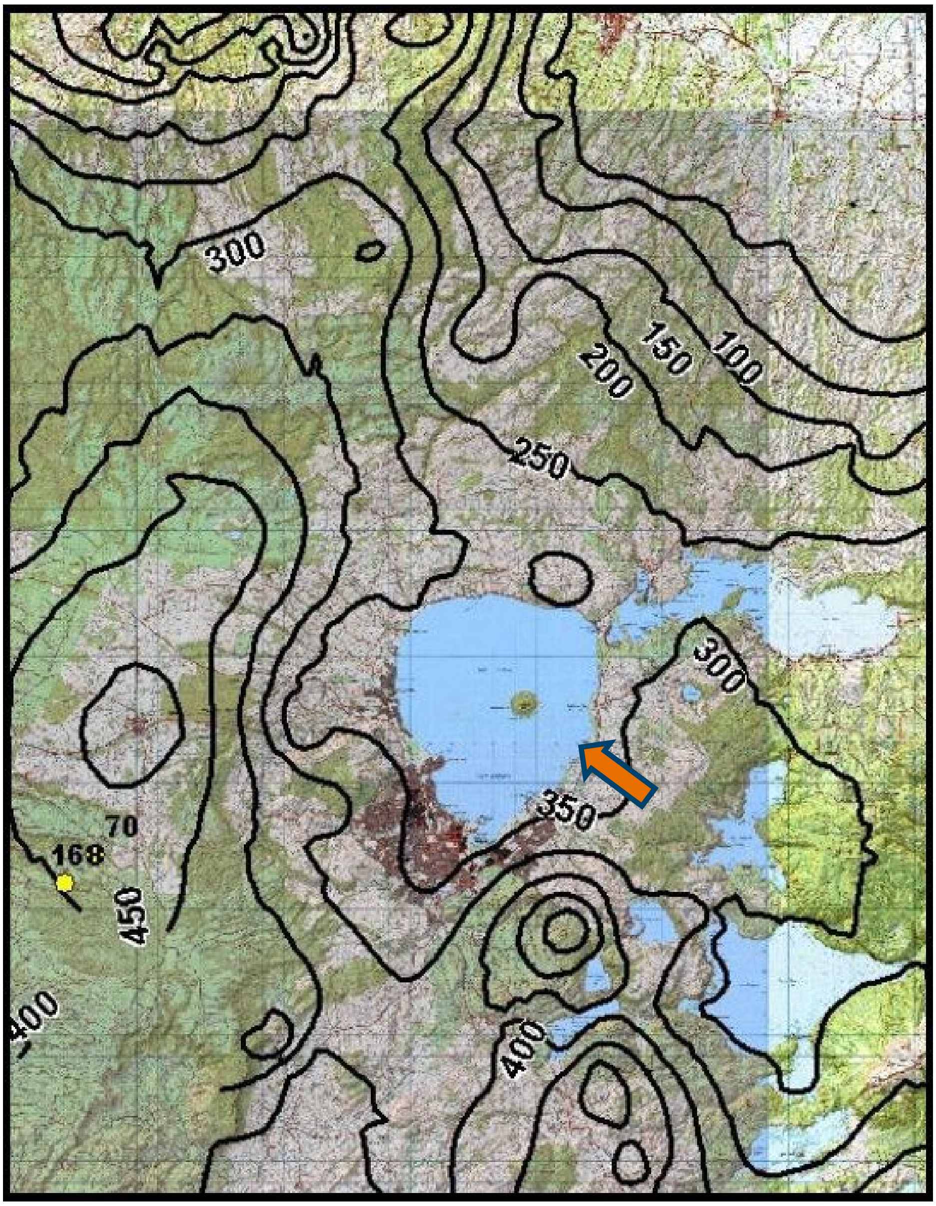

Figure 10: Potentiometric map of the Lake Rotorua Catchment (White et. al.*, 2004). Around Rotokawa, the top (~20 m) groundwater aquifer flows towards the lake (orange arrow), where it mixes with geothermal waters ascending from depth (Seward* et. al.*, 2019).*

2.4 Geophysics

Geophysical surveys are very effective to help characterise the geothermal aquifers, geology and fluid proprieties at subsurface. They are cost-effective specially compared to drilling, therefore are typically deployed for an initial ‘screening’ of the geothermal system. The results are used to map the approximate extent of the geothermal system and to determine the likely broad properties of the rocks and fluids at depth.

More detailed and sophisticated surveys are carried out at later stages to provide a more granular understanding of the conditions at subsurface. Those surveys are significantly more complex, costly and require highly specialised and skilled staff/geophysicists to gather quality data, process and interpret the results.

There are various geophysical survey methods available, all providing different information related to the properties of the geothermal water and geothermally altered rocks. Geophysical surveys typically involve deploying more than one method (e.g. resistivity and magnetics) to ensure a robust and reliable characterisation of the conditions at subsurface and build confidence on the results. The main methods used at the exploration stage in geothermal are the ones that measure the resistivity, magnetic and gravimetric properties of the ground.

Resistivity[1] is one, if not the key, ground property measured in geothermal applications. Resistivity results typically reflect a combination of the fluids proprieties (temperature, salinity and flow) and the clay content on the rocks (clay mineralogy and their relative abundance). Depending on how the survey is designed, the depth of penetration can be of many kilometres scale (e.g. > 10 kms), but normally the depths of interest for geothermal exploration are the top 1-3 km depth, the typical depth range of reservoirs tapped in New Zealand for power production.

Historic geophysical surveys have been carried out in the Rotokawa-Mokoia area over the last 50 years. A summary/inventory of the surveys is presented in Table 1 below.

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[1] The resistivity of the ground can be measured by several different methods on land and even downhole (well logging). Typical methods applied at surface (on land) are DC resistivity, TEM, MT and CSAMT. Downhole data has not been collected for any of the wells in Rotokawa, as this type of survey is typically deployed in larger developments, such as power plants for electricity generation, given the costs and complexity involved.

Table 1: Summary/inventory of the relevant geophysical surveys, the method(s) applied, broad area covered, key findings and the reference source

Year of publication	Survey type/method(s)	General survey location	Key findings	Reference source
1974	• DC resistivity (?) (original not be accessed)	Greater Rotorua area	• Identifies zones of low apparent resistivity/the geothermal aquifer around Rotokawa.	Macdonald (1974) *apud* Seward *et. al.* (2019)
1980-1981	• DC resistivity	Around Lake Rotokawa	• Refinement of the geothermal aquifer and delineation of the potential upflow just northeast of Lake Rotokawa.	Drolia (1980) Drolia *et. al.* (1981)
1992	• DC resistivity, including a review of historic datasets • Magnetics	Lake Rotorua area	• Low resistivity and demagnetised zone between Mokoia Island and Rotokawa. • High-resistivity/magnetic zone between the RMGS and the Rotorua City system, linked to the Hinemoa Point rhyolitic dome and its extension into the lake, potentially creating some barrier to fluid flow between the two systems. • Conceptual understanding of the Mokoia Island magmatic intrusion and its control on the discharge along the interface between the intrusion and the lakebed sediments.	Bibby *et. al.* (1992)
1992	• Heat flow	Bottom of Lake Rotorua	• Maps the warm zones between Mokoia Island and Rotokawa and pockets along the lake edge area between the Rotorua Airport and Rotorua City.	Whiteford (1992)
1992	• TIR (thermal infrared)	Mokoia Island	• Identifies the hot springs and seeps along the southeast shores of Mokoia Island.	Mongillo & Bromley (1992)
2006	• TEM (transient electromagnetic) sounding • MT (magnetotellurics) sounding	Mokoia Island	• Develops a more in-depth understanding of the 2D resistivity structure of eastern Mokoia Island.	Bromley *et. al.* (2006)

Year of publication	Survey type/method(s)	General survey location	Key findings	Reference source
2014	• Airborne TIR (thermal infrared)	Rotorua City area Rotokawa-Mokoia area	• Identifies anything that is hot (and cold), like hot springs, seeps, and warm ground. Covers most of the geothermal system at high resolution (~1 m^2).	Reeves *et. al.* (2014)
2022	• MT (magnetotellurics)	Wider Rotorua Lakes region and bottom of some lakes, including Lake Rotorua	• Imaging of the heat source that drives several geothermal systems around the wider Rotorua Lakes region. • For the Rotorua City and the Rotokawa-Mokoia geothermal systems, a magmatic plume was imaged at 5-8 km depth beneath Rotorua, connecting the 'roots' of both systems. • This suggests that the systems share the same deep heat source, but this does not necessarily imply that a hydrogeological connection exists.	Bertrand *et. al.* (2022)
2023	• Heat flow • Magnetics • Gravimetry	Bottom of Lake Rotorua	• Heat flow results show broad similar patterns of Whiteford (1992), but with greater detail/resolution. • Successfully identifies the high heat flow anomaly between Mokoia Island and Rotokawa. • Identifies a broad neck of above-background values between the Rotorua City and the Rotokawa-Mokoia systems, although slightly offset to northwest. • Confirms a demagnetised zone between Mokoia Island and Rotokawa (cf. Bibby *et. al.*, 1992). • Interpreted results still not published.	de Ronde *et. al.* (2023)

The key combined findings of the geophysical surveys and their implications for the understanding of the Rotokawa-Mokoia Geothermal System are listed below:

- *The outflow might be centred around the lake rather than around Rotokawa*: A low resistivity zone centred between Mokoia Island and the Rotorua Airport (Bibby *et. al.*, 1992) coincides with a zone of high heat flow measured and mapped by Whiteford (1992) and de Ronde *et. al.* (2023) and a magnetic low possibly controlled by demagnetisation of the volcanoclastic deposits beneath the lake due to hydrothermal alteration (Bibby *et. al.*, 1992; de Ronde *et. al.*, 2023) (Figure 12).
- *Fluid flow and controls on thermal activity in Mokoia Island*: The aeromagnetic survey results show that the Mokoia Island rhyolite dome apparently extends about 1 km to the east beneath the lake sediments (Bibby *et. al.*, 1992, de Ronde *et. al.*, 2023). The interface between the rhyolitic intrusion and the lakebed seems to provide a more permeable pathway for the ascent of geothermal fluids, compared to through the matrix of the rhyolite or the lakebed sediments, as supported by geochemistry (Glover, 1974; Section 2.5). The location of the geothermal surface features of Mokoia Island is inferred by Bibby *et. al.* (1992) to be controlled by this interface; however, it is likely that the lake level/head also controls the discharge location, as observed elsewhere (e.g., Lake Rotoiti, Lake Tarawera).

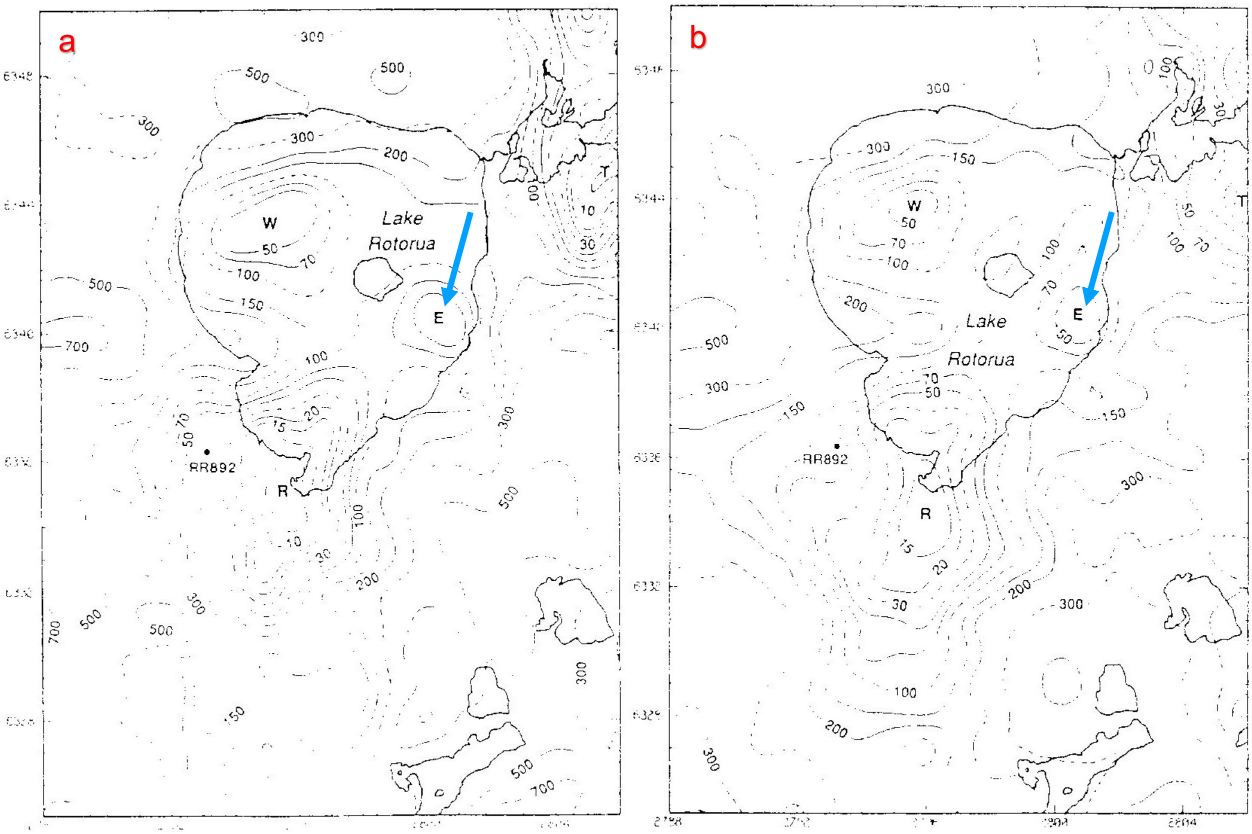

Figure 11: Location of the centre of the geothermal system, based on different geophysical datasets (blue arrows). (a) and (b) shallow and deep resistivity (~250 m and 500 m depth, 500 m and 1000 m Schlumberger nominal spacing), respectively. After Bibby et. al. *(1992).*

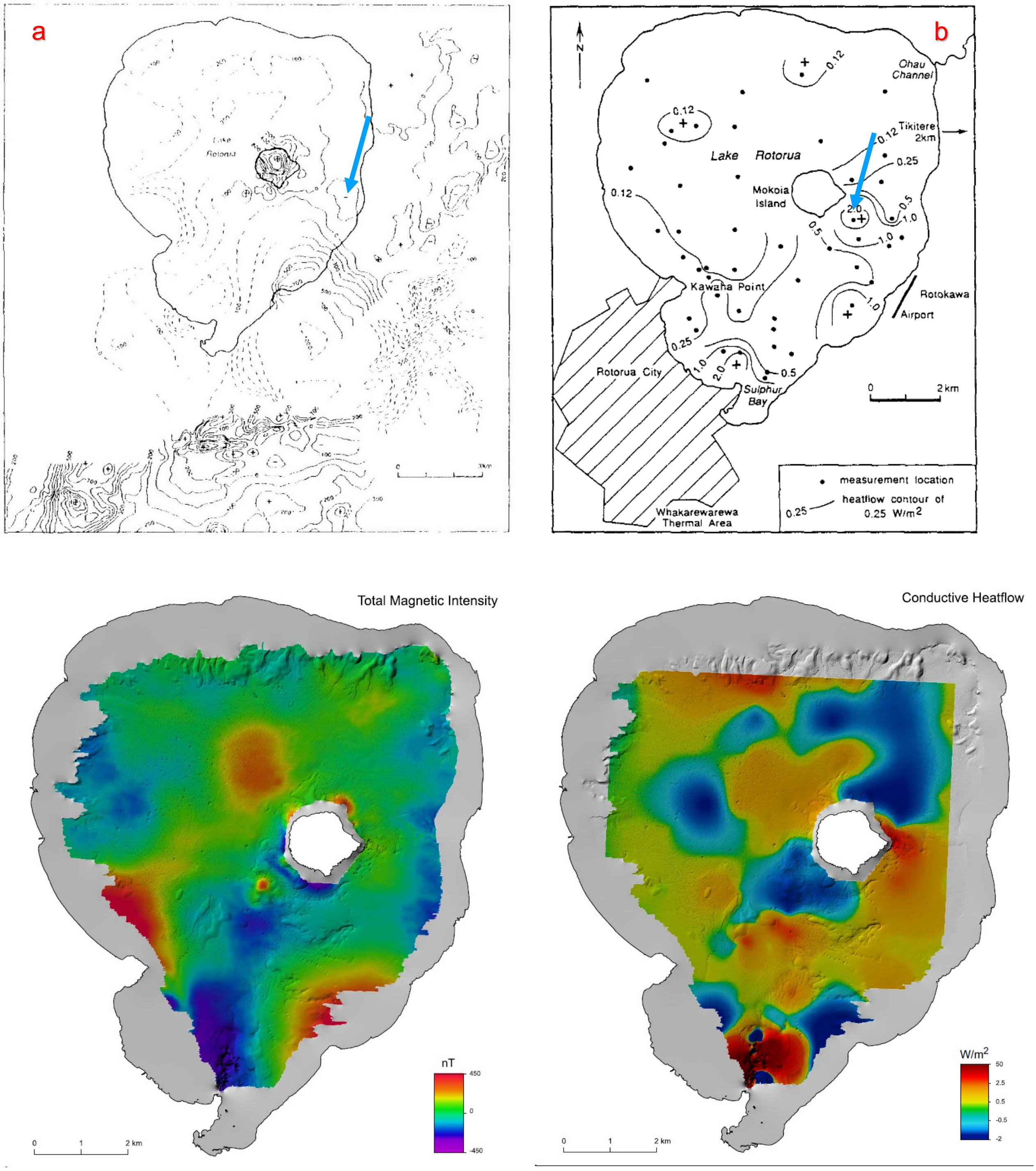

Figure 12: Location of the centre of the geothermal system, based on different geophysical datasets (blue arrows). (a) and (c) Aeromagnetic field (nT). (b) and (d) bottom of the lake heat flow (W/m^2). After Bibby et. al. (1992) and de Ronde et. al. *(2023).*

2.5 Geochemistry and geothermometry

This section summarises the state of knowledge and data available on the chemistry of the Rotokawa-Mokoia Geothermal System. Geochemical surveys are key to understanding the characteristics of the geothermal water and how they relate to various physical processes, as below:

- Identify/monitor various aquifer processes of interest for the management of a geothermal system, including potentially adverse ones.
- Classify the features in broad water-types (e.g. alkali-chloride, alkali-sulphate). Different types of features mean different things for the understanding of the hydrology of the system.
- Determine the source of water for different features (e.g. whether different features are fed by the same outflow).
- Forecast the temperatures at depths based on various geothermometers.

The chemistry of the springs at both Rotokawa and Mokoia Island, and wells in Rotokawa, shows that they consist of generally dilute, neutral, sodium chloride water. This chemistry indicates interaction (dilution) with the shallower groundwater system. Drolia *et. al.* (1981) estimates that cold groundwater may make up for more than 80% of the mix.

The chloride-to-boron ratio is similar in both Rotokawa and Mokoia Island areas too (~40-46 parts of chloride to 1 part of boron), indicating that the same deep aquifer feeds both areas (i.e. a single source of fluids; Glover, 1974). The thermal springs at Mokoia Island also has a chemical signature that suggests limited rock-water interaction (Glover, 1974).

Chemistry data from wells and springs presented in Drolia *et. al.* (1981) and from the BOPRC consents/compliance data are presented as a ternary diagram in Figure 13. The Māori Bath Spring and wells 4 and 6 are enriched in chloride compared to both the airport and Wharenui springs (and Hinemoa Pool, *Figure 13*). Wells 4 and 6 of Drolia *et. al.* (1981), Well LR904 (Rotokawa School), an unnumbered well at 830 Te Ngae Road and the Māori Bath spring are all classified as mature geothermal waters. Wharenui Springs represent peripheral waters and the Airport Spring sits within the interface zone between peripheral waters and steam heated waters, but the chemistry results for the Airport Spring should be used with caution.

Geochemistry data from Hinemoa Pool indicates little to no change in chemistry and temperature over time. The data points are very widely spaced, (four to five data points only over 60-plus years), therefore, any inferred trend or relationship should be treated with caution. The results are summarised below:

- All cations and anions are stable over time (e.g. sodium, chloride).
- The bicarbonate data, however, is more varied with two data points showing a ~75 ppm concentration change over the last ~10 years (with previous data points showing no change over ~20 years).
- While the pH has slowly and consistently increased over time, those changes are considered minimal and do not characterise a change in geothermal water-type (i.e. it stayed within the range of near-neutral waters).
- Finally, the temperature has been stable over the last 40-plus years at ~ 55°C, other than an anomalous reading (~43°C) in the early ‘90s.

Downhole temperature measurements indicate that the geothermal aquifer is up to 115°C at up to 100 meters depth (Figure 9). However, geothermometer calculations used to estimate the temperature of the geothermal water at greater depths indicate that the source geothermal aquifer(s) are hotter than the relatively shallow aquifer currently tapped, as expected.

Based on the chemistry of Well 11 of Drolia *et. al.* (1981), which likely corresponds to Well LR904 in the BOPRC database, the deeper geothermal aquifer is most likely at about 200°C (T_{NKC} geothermometer Mg corrected, using Powell & Cumming, 2010 calculator). This geothermometer (T_{NKC}) reportedly has a good match with measured well temperatures in deep geothermal wells (Powell & Cumming, 2010).

Based on the slow equilibrating $T_{Na/K}$ geothermometer (Nieva & Nieva, 1987, Fournier, 1979 and Giggenbach, 1988), temperatures could be in the range of ~270-290°C at greater depths, however, this geothermometer reportedly overestimates the reservoir temperatures (Powell & Cumming, 2010).

Note that Drolia *et. al.* (1981) estimated source fluids at 315-355°C, probably based on $T_{Na/K}$ geothermometer of Tonani (1980), which clearly overestimates temperatures compared to improved $T_{Na/K}$ geothermometers (Can, 2002). Further work would help to refine the geothermometry of the system and better understand the temperature of the geothermal fluids from different hydrological units, at greater depths.

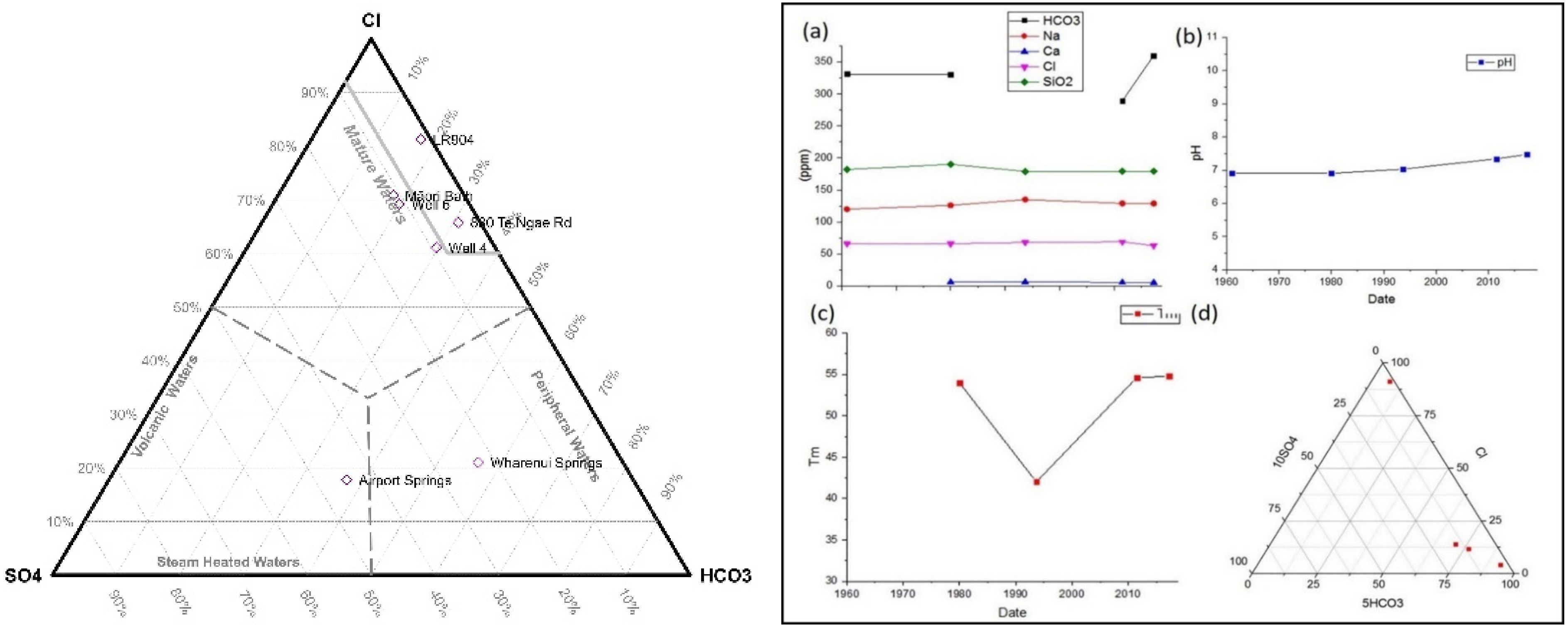

Figure 13: Cl-SO_4-HCO_3 ternary plot and water-types for selected wells and springs around Rotokawa (left). Chemistry data from Hinemoa Pool in Mokoia Island. Data collected and collated by GeoNet, graphs from Seward et. al. (2019) (right).

2.6 Rotokawa-Mokoia Geothermal System extent and potential hydrological connection with the Rotorua City Geothermal System

This section outlines the key information utilised to determine the likely spatial extent of the Rotokawa-Mokoia Geothermal System and its potential hydrological connection with the Rotorua City system.

As described in Section 2.1, the thermal areas inland, beneath the lake and at Mokoia Island are the surface expression of a single, continuous geothermal system at depth[2]. Building on this understanding, Zuquim et. *al.* (2023) looked into utilising the geoscientific datasets publicly available and applying a methodology to map the extent of the geothermal system and the area of potential hydrological connection with the Rotorua City system.

The key datasets utilised to determine the geographical extent of the system for the RMGS are geophysics (heat flow, resistivity and magnetics), geochemistry, location and extent of the thermal areas, well data and the geological-structural setting. The geographical extent of the Rotokawa-Mokoia Geothermal System and the potential area of connection with the Rotorua City system is presented in Figure 4.

Bibby *et.al.* (1992) provides some justification around the potential hydrological connection between the Rotokawa-Mokoia and the Rotorua City systems. Bibby *et.al.* (1992) interpretation of the geophysical results relevant to the potential hydrological connection between the Rotokawa-Mokoia and the Rotorua City systems is reproduced in full below. It is important to note that, within this area of potential hydrological connection between the two systems, warm geothermal water may exist at reasonably shallow depths (a few hundred meters), but might not be of sufficient temperature, for example, to develop the strong geophysical signature typical of other high-temperature systems in Aotearoa New Zealand (Bibby *et.al.*, 1992; Zuquim & Box, 2023).

"*Within this neck, heat flow values are slightly elevated, although distinctly lower than those of either geothermal system. Magnetic* measurements (reproduced in Figure 12a; cf. Figure 12c) *suggest that the rhyolite outcropping at Hinemoa Point extends into the lake with at least part lying beneath the lower resistivity neck. If fluids of geothermal origin are present between the two systems at shallow depths, it would be expected that hydrothermal alteration would reduce the magnetism of the rocks between the systems. Thus, the existence of a high magnetic signal in this region is suggestive of the lack of movement of fluids between the systems. Hence, we suggest that the East Lake Rotorua Resistivity Anomaly*[3] *marks an independent geothermal system with an area of about 8 km*^{2}*. At depths beyond 1 km, the proximity of the systems is such that fluid connections (…) are bound to exist between the systems. It is possible that at such depths, a common source region may supply fluid to both systems.*" (after Bibby *et.al.*, 1992)

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[2] Note that this hydrological connection between the Rotokawa and the Mokoia Island areas is already acknowledged in the BOPRC planning framework, by treating both areas as one geothermal system under the RNRP and RPS.

[3] The East Lake Rotorua system of Bibby *et.al.* (1992) is equivalent to the Rotokawa-Mokoia Geothermal System.

3 Monitoring

Currently, environmental monitoring of the geothermal system is limited to monitoring environmental factors that could control the state of the geothermal system, rather the monitoring of the geothermal system *per se* (e.g. monitoring the geothermal aquifer and surface features). Rainfall, lake levels and groundwater levels are all known to exert some control on the geothermal system aquifer and the associated surface features health and activity. Infrequent monitoring of the Hinemoa Pool (Mokoia Island) is carried out by GeoNet. The monitoring results are presented in Section 2.5.

The Rotokawa-Mokoia Geothermal System overlaps with the Waingaehe and Waiohewa surface water catchments. Flow data from both of these catchments could be used to understand some environmental controls on the geothermal system in the future. Data from two BOPRC groundwater monitoring bores could be also used for such analysis (Figure 14). The National Institute of Water and Atmospheric Research (NIWA) also has a long-term rainfall station at the Rotorua Airport. This station is closer to the geothermal system than the BOPRC ones at Tikitere to the northeast.

Currently, there is limited data available on consent monitoring. To understand patterns and changes in use, and correlate these changes with potential changes in the geothermal system, would be challenging and have high levels of associated uncertainty.

To summarise, there is substantial environmental monitoring data in the area to understand environmental controls on the geothermal system. However, there is effectively limited geothermal monitoring data to compare/correlate against those other environmental datasets. An analysis of those environmental datasets is beyond the scope of this report but could be part of the upcoming review of the BOPRC Natural Environment Regional Monitoring Network (NERMN).

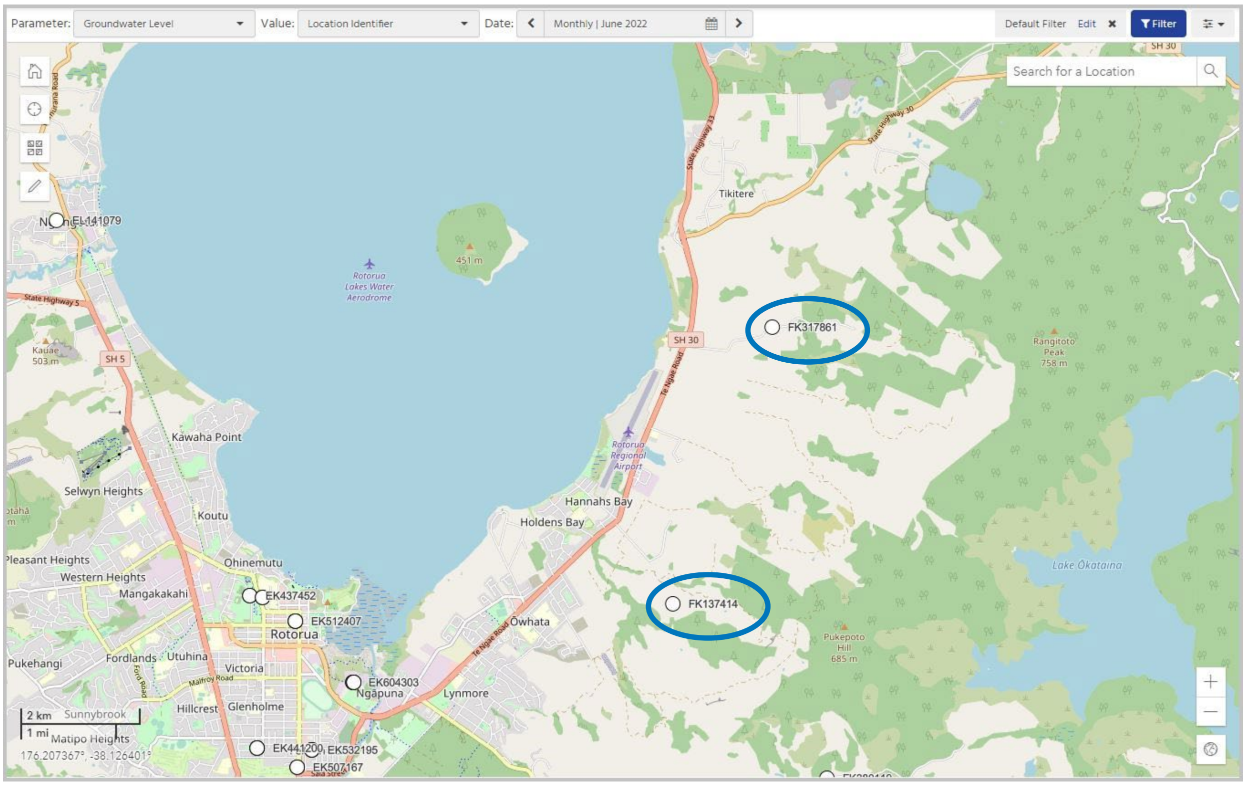

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Figure 14: BOPRC groundwater monitoring sites in the vicinity of the geothermal system.

Part 2:
Use

1 Introduction

Both geothermal and groundwater takes can affect a geothermal system, such as the RMGS. Geothermal wells tap directly into the geothermal aquifer and can reduce/change the temperature, pressure and chemistry of the aquifer, depending on how and how much geothermal water/energy is extracted from the geothermal aquifer/hot rocks.

Some takes are so small that their effects, individually or cumulatively, are likely to be negligible or minimal. However, larger takes or a large combined level of take by several small users have the potential to cause more significant, material adverse effects to the system.

Groundwater takes in proximity to the system could, theoretically, also affect the geothermal system by affecting the pressure of the surrounding groundwater aquifer. This would have the potential to interfere with the recharge to the geothermal system and/or with the geothermal surface features dynamics.

2 Geothermal and groundwater takes

There are currently three active consented geothermal takes from the RMGS, and five groundwater takes in relatively close proximity to the system. Two of those takes are for domestic use and one for municipal use at Rotokawa School. Their location and resource consent references/numbers are presented in Figure 15.

A summary of the information available on geothermal takes and selected groundwater takes is presented in Table 2 and Table 3, respectively. A stocktake of the consented and estimated actual use (geothermal energy and water) from the system is presented in Table 4.

About 81 tonnes per day is consented to be used for space and water heating, cooking and for mineral pools use. It is estimated that the actual use matches closely to what is currently consented (Table 4).

The estimated amount of heat extracted from the geothermal system (net heat take) is about 6.4 megawatts-hour thermal ($MW_{th}.h$) per day. This estimate assumes that the heat is extracted continuously (i.e., 24 hours a day, 7 days a week, 365 days per year), which is likely an overestimate to the yearly take. However, there is currently not enough information to understand how the takes vary on a daily, weekly, monthly and/or seasonally to more accurately construct the take profile for an annual period.

As described before, theoretically, the groundwater takes could affect the geothermal system, depending on several factors like groundwater flow pathways, take size, rate, depth and distance from the geothermal system. This is because groundwater takes near the geothermal system can lower the groundwater table and, secondarily, affect groundwater recharge to the geothermal system. Changing the groundwater system state could therefore affect the mixing patterns with geothermal fluids on shallower and deeper levels and could have a noticeable adverse effect on the physical-chemical attributes of the geothermal surface features.

In the case of the RMGS, groundwater takes in the vicinity of the system, individually and cumulatively, are quite small, and there are no consented groundwater takes within the system extent. Those takes around the system are located ~3 km from the thermal area of Rotokawa or ~2 km from the mapped edge of the system (cf. Figure 4), thus are expected to have a negligible effect on the geothermal system aquifer and surface features, both individually and cumulatively.

Groundwater take 65786 is relatively close to the northern boundary of the system (cf. Figure 4), however, this take is also located quite a distance away from the thermal features in Rotokawa (~2.5 km) and downstream of the regional groundwater flow. Therefore, the potential adverse effects to the geothermal system are also considered negligible.

Figure 15: Location of geothermal takes from the Rotokawa-Mokoia Geothermal System and cold groundwater takes in the vicinity of the geothermal system.

Table 2: Consented geothermal takes from the Rotokawa-Mokoia Geothermal System.

Consent (project) number	Purpose (amended)	Type of use	Production well number	Well depth (m)	Casing depth (m)	Production well temperature (°C)	Reinjection well number	Reinjection well depth (m)	Reinjection temperature (°C)
67314	Space and water heating, mineral pools	Domestic	830B Te Ngae Road	58 (based on data from Drolia *et. al.*)	unknown	65.3	n/a - discharge to Lake Rotokawa	n/a	n/a
RM21-0163	Space and water heating, mineral pools and cooking	Domestic	RR11552	38	24	92.7	n/a – soak holes	n/a	n/a
RM22-0201	Space and water heating	Municipal school	LR904	38	32	100	BN-4565	32	60

Table 3: Consented groundwater takes around the Rotokawa-Mokoia Geothermal System.

Consent number	Distance from Lake Rotokawa (m)	Maxtotal water (t/day)	Production bore number	Production bore depth (m)	Production bore cased depth (m)
65786	2845	116.4	BN-2119	30	17
RM19-0413	3022	146.8	BN19-0120	57.0	28.0
21632	2730	69.9	BN20-0202	unknown	unknown

Table 4: Geothermal heat and water use (actual estimated and consented) from the Rotokawa-Mokoia Geothermal System.

Consent (project) number	Energy use - Actual (kW.h per day)	Energy use - Consented (kW.h per day)	Fluid use - Actual (tonnes per day)	Fluid use - Consented (tonnes per day)	Geothermal fluid discharged to waste (tonnes per day)	Fluid to waste (max) from mineral pools (tonnes per day)	Receiving water body
67314	1291.8	1216.4	17.0	16	16	Unknown	Lake Rotokawa
RM21-0163	3713.4	3777.2	34.4	35	35	3	Shallow groundwater
RM22-0201	1369.6	1398.7	29.4	30	0	n/a	Source geothermal aquifer
TOTAL	**6374.8**	**6392.3**	**80.8**	**81.0**	**51**	**3**	

3 Discharges and waste

Currently, none of the three active geothermal takes from the RMGS have the same method of discharge after use (Table 2). The two takes that have a component of mineral pool use (i.e. in addition to use for space and water heating, and cooking) discharge to the surface environment; one discharges to shallow groundwater via soak hole and the other one to Lake Rotokawa. The third take discharges back to the geothermal aquifer it produces from via an injection well (i.e. by reinjection).

About 51 tonnes per day (t/day), or 63% of the water extracted from the geothermal aquifer, is discharged to waste[4]. Based on data from the three takes in Rotokawa (which is 100% of the consented extractive takes), about 3 t/day of the water extracted by wells is used for mineral pools, equivalent to ~6% of the ~51 t/day discharged to waste.

Note that reinjection of geothermal water that has been bathed-in is typically a constraint for reinjection. This is due to potential environmental effects associated with cooling of the geothermal aquifer and chemical and pathological contamination (Sajkowski *et. al.*, 2022) and cultural issues. Therefore, there may be opportunities to increase the efficiency in extractive use/reduce net loss from the system from ~60% (estimated) to ~95% of the water extracted by wells.

Finally, Rotokawa School is the only user with discharge via reinjection. This consent holder reinjects 100% of the water extracted after harvesting some of the heat available. The fact that the cooled water with some residual heat is returned to the aquifer after use significantly reduces the net heat take (or heat waste). This discharge method also avoids land, surface water and shallow groundwater contamination.

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[4] Water discharged to the surface environment after use does not return to the geothermal aquifer it originally produced from, even if by soakage hole.

Part 3:
Final remarks

1 Gaps and potential future work

As described in Section 2.1, the exploration and scientific surveys of the mid-1970s to early 1990s yielded a significant amount of information on the Rotokawa area of the geothermal system and the bottom of Lake Rotorua between the Airport and Mokoia Island. More recent surveys have yielded additional information, particularly around Mokoia Island and the heat source for the geothermal system at several kilometres depth.

While these new surveys have significantly improved Council's understanding of the geothermal system, this new knowledge is yet to be translated into an integrated, comprehensive and updated conceptual model.

Geothermal environmental monitoring and consents monitoring data is limited. Currently, there is not enough data (quality and quantity) to determine the state and trend of the RMGS, or to understand how the system responds to natural and anthropogenic effects and potential stressors.

For example, with the current data available, it is not possible to correlate past changes in the geothermal system state with past changes in levels or patterns of use, or correlate changes in the state of the system with changes in rainfall or lake/groundwater levels, all of those factors being known to influence or control the geothermal system activity or state.

Considering the current pressures on renewable sources of energy like geothermal, and the BOPRC policy provisions to protect significant geothermal surface features (estimated ~12 out of the 15 features of the RMGS; Reeves, 2020), improved environmental and consent monitoring could be considered following the development of a robust conceptual model.

A future monitoring would likely involve monitoring the geothermal surface features, the exploited aquifer at ~50-100 m depth and, potentially, a deeper aquifer less influenced by groundwater (e.g. > 200 m depth) (Seward *et. al.*, 2019). A summary stocktake of the data and gaps is presented in Table 5 and recommendations are presented in Table ***6***.

Table 5: Summary stocktake of the data available (cf. Table 6). Colour coded to the assessed level of data quality/quantity (green = fit-for-purpose; orange = requires improvement; red = not available/very low quality/quantity).

Area	**Geothermal surface features**		**Geothermal monitoring wells (cf. Table *6*)**		***Ad hoc* surveys**[5]	**Consents monitoring**	**Other datasets**		
	Survey	**Monitoring**[6]	**Survey**	**Monitoring**			**Lake level**	**Groundwater**	**Climate**[7]
Rotokawa	Inventory available.	Not currently done.	Historical published and more recent datasets (from consents/ compliance) available.	Not currently done.	**Heat flow**: Not available **TIR**: Available, does not cover the northern end of the system **Aerial imagery**: Available (BOPRC, Retrolens, Photoblique).	Very limited current and historical data on actual use.	N/A	Two (2) BOPRC groundwater monitoring sites in the area).[8] No shallow bore in-field.	OK. NIWA/Metservice climate station at the Rotorua Airport (Rotorua Aero Aws). Data since 1981.
Mokoia	Same as above.	Same as above.	N/A	Same as above.	Same as above	N/A	N/A	Not currently done.	Not currently done.
Lake Rotorua	Potential seeps and vents at the bottom of lake not fully identified/ proved.	N/A	N/A	N/A	Detailed heat flow survey - bottom of the Lake completed and published.[9]	N/A	BOPRC station FL150407. Data since 1952.	N/A	N/A

Table 6: Recommendations to fill the data/monitoring gaps (cf. Table 5). Colour coded as per Table 5.

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[5] Heat flow, TIR, LIDAR/Aerial imagery.

[6] Physical attributes (temperature, flow/water level, etc) and chemistry.

[7] Rainfall, MSL pressure, wind speed, air temperature.

[8] FK317861 just north of the geothermal system has water level data since 1995. Bore BN-4005 is 180 m deep and cased to 167 mD. FK137414 just south has water level data since 2017. Bore BN-10968 is 43.1 m deep and cased to 39.4 mD.

9 de Ronde et. al. (2023).

Area	**Geothermal surface features**		**Geothermal wells (cf. *Table 6*)**		***Ad hoc* surveys**	**Consents monitoring**	**Other datasets**		
	Survey	**Monitoring**[10]	**Survey**	**Monitoring**[1]			**Lake level**	**Groundwater**	**Climate**
Rotokawa	UPDATE/ GROUND TRUTH (TIR could guide re-surveying).	Recommend set up a monitoring plan after the resurveying has been completed. More high-frequency to start with (e.g. monthly), then could be spaced (e.g. bimonthly), depending on the results.	Compile information available and update BOPRC database	Recommend establishing at least 2 dedicated monitoring bores after updating the conceptual model, probably ~100-150 m deep. Monitor water level, temperature, chemistry regularly.	**Heat flow**: Carry out **TIR**: Re-survey every 10 years, cover far north next time. **Aerial imagery**: N/A	Require and record annual bucket-stopwatch and production-reinjection temperature data over winter months. Require net loss data for daily and monthly use.	N/A	Establish a shallow monitoring well in-field (5-10 mD).	OK
Mokoia	Same as above.	Same as above.	N/A	Same as above.	Same as above.	N/A	N/A	Same as above.	Not currently done.
Lake Rotorua	Identify/ monitor hot water/gas discharges at the bottom of lake(?).	N/A	N/A	N/A	Geophysical data still not publicly available.	N/A	OK	N/A	N/A

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[10] As per methodology and principles of Scott (2012). Shall include Lake Rotokawa, Māori Bath spring, Hinemoa pool as minimum.

2 Summary and conclusions

A summary of the key information presented in the report and the main conclusions are presented below:

- There is currently a reasonable level of scientific knowledge around the extent and nature of the RMGS. However, this knowledge is not captured in the conceptual model currently available for the RMGS. This is because the model was developed in the early 1980s, prior to most key geoscientific surveys in the area. This knowledge is thus yet to be translated into an updated, robust conceptual model for the system.
- The development of an updated conceptual model will be key to inform the management of the system, including any future use direction and environmental monitoring programme.
- Currently, geothermal environmental monitoring and consents monitoring is limited. From the data available, it is not possible to determine the state and trends of the RMGS, neither correlate changes in state with changes in use, if present. Improved monitoring would help to overcome those issues, and is a matter that is being considered by BOPRC.
- Current levels of use of geothermal water and energy is very low: ~81 t/day (water gross take) and ~6.4 MW_{th}.h per day (heat net take). However, based on the current data available, the RMGS is likely a small system. Therefore, it is difficult to determine what this low level of use means to the health of the geothermal system and its surface features. An assessment of the size of the resource would help to understand opportunities for sustainably use, while protecting the significant geothermal surface features.
- About 60% of the geothermal water extracted from the shallow geothermal aquifer via production wells is currently discharged to waste (net mass loss). Opportunities for increased support of the health of the geothermal aquifer through reinjection could be explored.

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