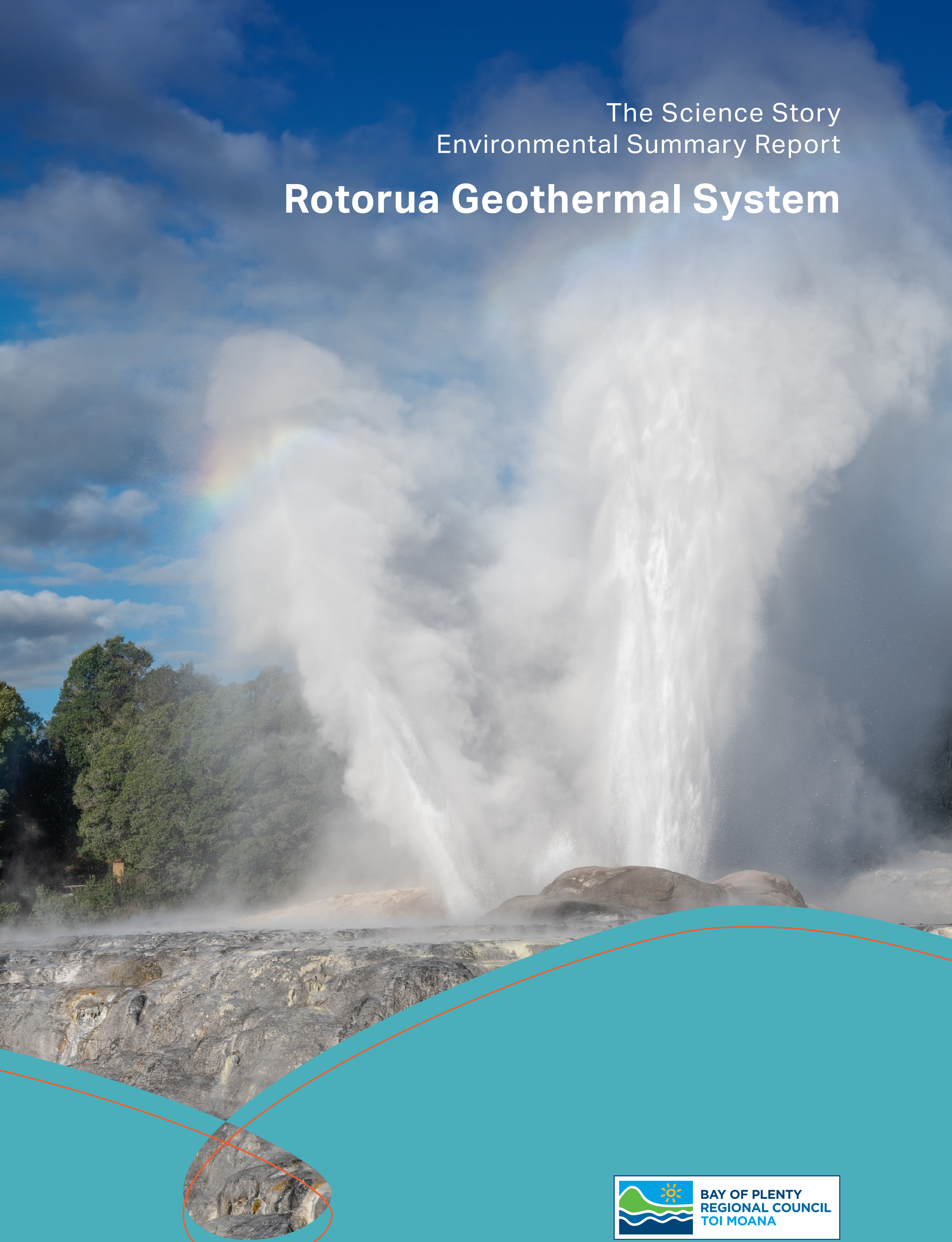
The Science Story
Environmental Summary Report

Rotorua Geothermal System



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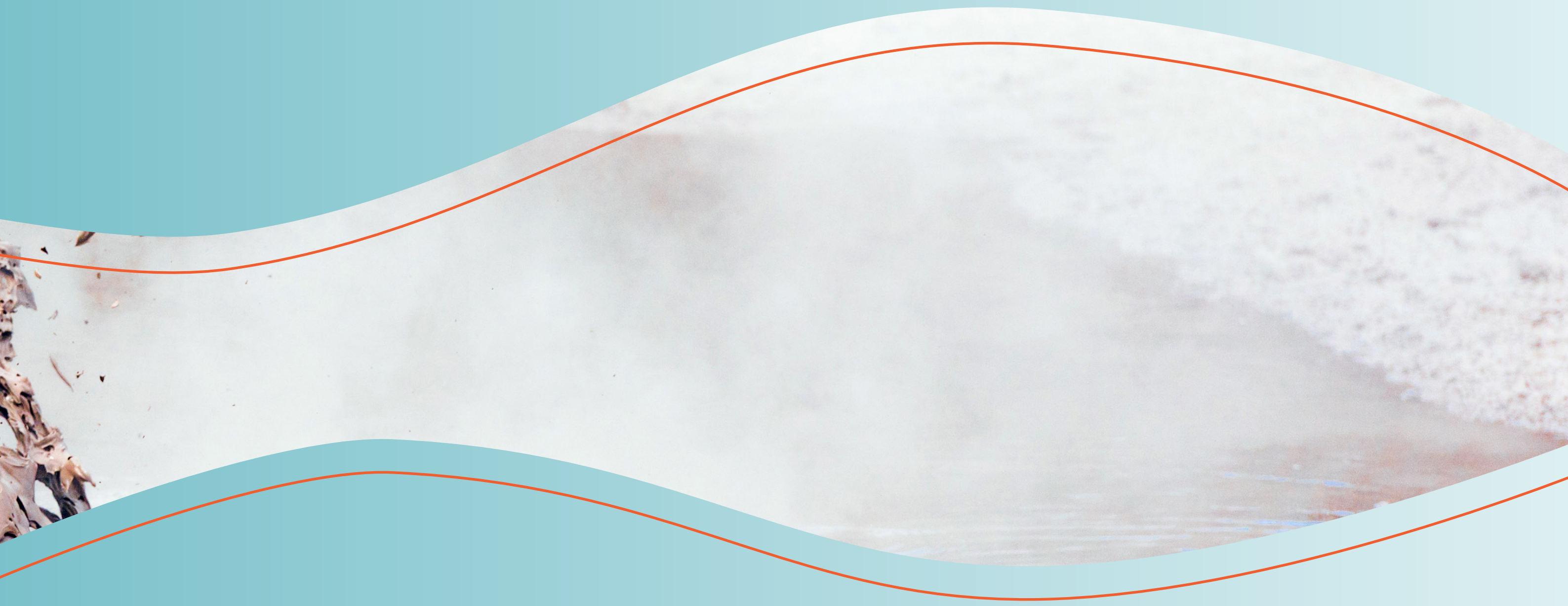
Environmental Summary Report

Rotorua Geothermal System

This report was prepared by Brad Scott
GNS Science - July 2019



The Bay of Plenty Regional Council is implementing a review of the Rotorua Geothermal Regional Plan and the Regional Natural Resources Plan to give effect to the Bay of Plenty Regional Policy Statement.

This report informs the regional plan review and describes the Rotorua Geothermal System, the current scientific knowledge of the geology, geophysics and chemistry. Also presented is a summary of the current state and trends for the geothermal aquifer, surface geothermal features, and current use of the system. Details of modelling and other monitoring and research is also presented. Detailed information on which this summary is based can be found in the reports in the reference list.

PART 1

Description of the Resource

Regional Geology Setting

The Rotorua Geothermal System is one of 12 systems in the Bay of Plenty Region and is a by product of volcanic activity in the Taupō Volcanic Zone. The Taupō Volcanic Zone geological landscape is dominated by eight calderas, where volcanoes collapsed inwards, in contrast to the volcanic cones of Tongariro National Park. The Taupō Volcanic Zone extends from Whakaari-White Island in the Bay of Plenty, southwest to Mount Ruapehu. The zone is characterised by very high heat flow, which supports the presence of geothermal systems.

Geothermal systems occur in areas having high heat flow, usually related to large scale volcano complexes.

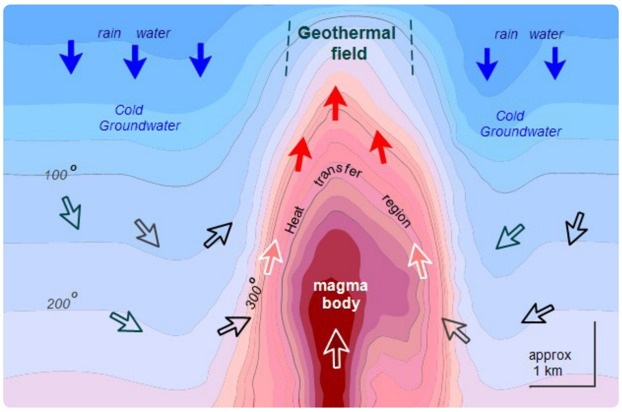


Figure 1 - Schematic showing how a geothermal system is created.

Their formation requires the existence of three important components: fluids, heat and permeability through rocks so that fluids can circulate. These conditions are met in many areas within the Taupō Volcanic Zone. Rotorua is one example.

The Rotorua Geothermal System underlies part of Rotorua City, from the southwestern end of Lake Rotorua to the Whakarewarewa Valley.

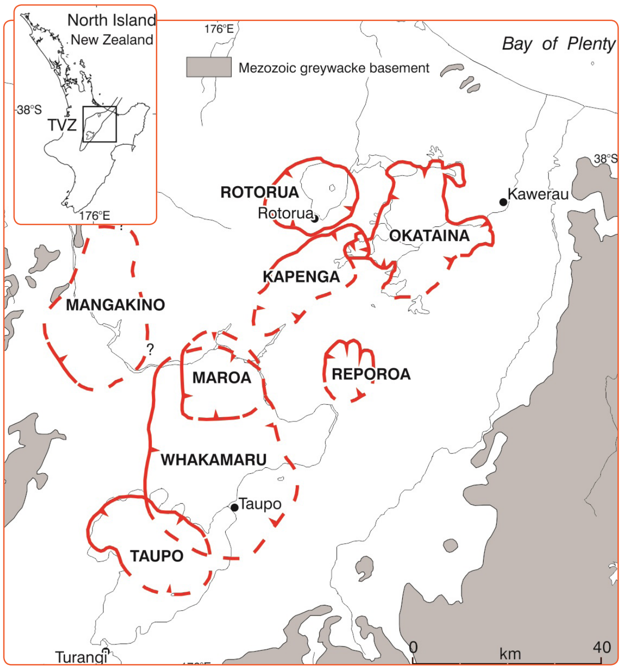


Figure 2 - Map of the central portion of the Taupō Volcanic Zone showing the eight calderas (after Nairn 2002).

The Rotorua Geothermal System

Surface geology, shallow bore hole data and geophysical data give us an understanding of the structures that control the Rotorua geothermal aquifer. Pyroclastic flows from the eruption that formed the Rotorua basin (caldera) 230,000 years ago deposited about 200 cubic kilometers of volcanic material (ignimbrite). Lava dome building eruptions followed for about 100,000 years leading to features such as Mt Ngongotaha, Mokoia Island, Owhatiura and Pukeroa hill. Erosion has also deposited thick layers of sediment into the basin.

There are three key rock types: the ignimbrite; lava of the lava domes; and sediments deposited on the floor of the Rotorua caldera.

When the Rotorua caldera collapsed several large fractures (faults) formed in the thick ignimbrite rocks controlling the upward flow of primary geothermal fluid. On the eastern side the major upflow feature is the Ngapuna Fault that runs northward from Whakarewarewa to Sulphur Bay. Across the southern area the structure is complex, dominated by the Inner Caldera Boundary Fault and the Roto-a-Tamaheke Fault. These and other recognised faults feed fluids to the surface features at Whakarewarewa.

Two lava domes that lie over the ignimbrite dominate the geology in the north and west. Pukeroa in the north reaches the surface at Hospital Hill and influences the formation of the surface features at Kuirau and Ohinemutu. South of Pukeroa is a buried lava dome, Railway Dome. Both lava domes are cracked and broken allowing the flow of primary fluids towards the surface.

The subsurface system covers about 12 km²; similar in extent to the surface expressions of springs and hot ground. The system also extends about 2 km north under the lake and south of Whakarewarewa.

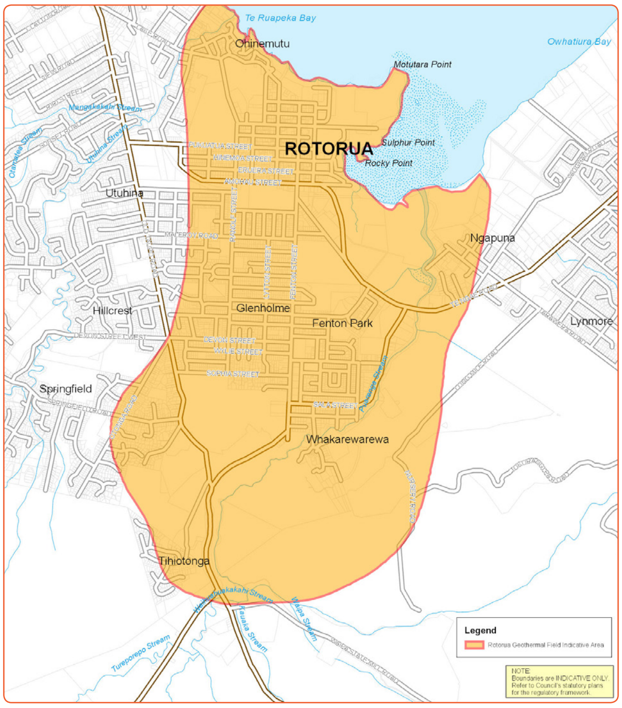


Figure 3 - Indicative boundary of Rotorua Geothermal System.

Deep survey work indicates near vertical boundaries along the northern and eastern sides and a more complex southern boundary. The new deeper resistivity picture from magnetotelluric surveys defines a very deep conductive zone that rises to within about 2.5 km depth and underlies the southern boundary.

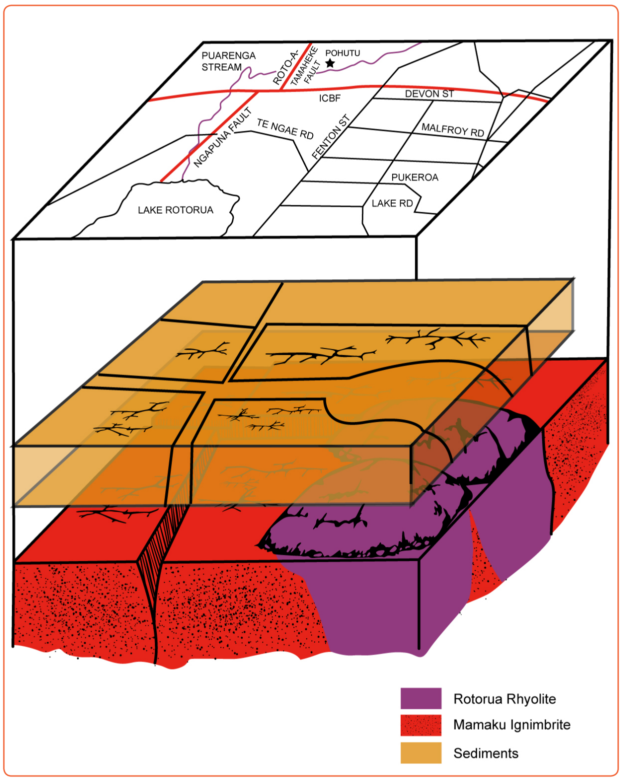


Figure 4 - Block diagram showing major geological and structural features of the Rotorua Geothermal System.

Surface Features

About 1500 geothermal surface features are recorded at the Rotorua Geothermal System, including some of New Zealand's last remaining geysers.

There are a wide variety of geothermal feature types. The Bay of Plenty Regional Policy Statement defines four feature categories. There are also three habitats associated with surface geothermal features; the aquatic one (springs and steams), the terrestrial one (warm and heated ground) and the micro-climate atmosphere.

Table 1 describes the physical and associated habitats of these features.

This link is to a video taken in Rotorua describing and featuring these geothermal features.

https://www.youtube.com/watch?v=CdNi43qQa7o

The Legend of Ngatoroirangi

The geothermal resources of the greater Rotorua-Taupo area are attributed in local legend to Ngatoroirangi, the Tohunga (priest) of the Te Arawa canoe who journeyed from Hawaiki inland from Maketu on the Bay of Plenty coast, through the Rotorua-Taupo area to Tongariro (Mt Ngauruhoe).

Primary Fluid type, alkaline chloride pools: A geothermal spring which maintains a continuous (or regular intermittent) overflow of chloride-enriched primary geothermal water, or, a depression, that naturally receives primary geothermal waters from depth. These are very likely to be sinter-lined and deposit sinter in the overflow channel. The waters in the pools will be clear and hot. The geysers of Rotorua are primary fluid features.

Mixed fluid type, mixed chemical pools: A geothermal spring which has an overflow of mixed geothermal fluid (chloride-enriched water and ground water) or a depression that naturally contains mixed geothermal waters. The waters will be coloured and maybe milky.

Steam heated type: Steam rising from depth mixes with ground water to make acid waters. This results in the grey pools and when soils and clay are included the mud pools form.

Heated Ground: A ground area that radiates heat from underground geothermal sources, discharging steam, diffusively through surface soils. If the steam flow is strong enough a fumarole may form.

Table 1 - Geothermal features - main types and associated habitats.

GEOTHERMAL FEATURES - MAIN TYPES AND ASSOCIATED HABITATS				
Discharge Energy HIGH	**1** Geysers	**4** Intermittent or active hydrothermal eruption craters	**7** Mud geysers	**10** Fumaroles
↕	**2** Flowing springs	**5** Mixed springs	**8** Ejecting mud pots	**11** Steaming ground
LOW	**3** Non flowing pools	**6** Mixed pools	**9** Mud pools	**12** Heated ground
	Primary geothermal fluid	Mixed / diluted geothermal fluid	Mixed / diluted steam heated fluid	Steam Fed
Geothermally-influenced aquatic habitat				
Geothermal habitat on heated ground				
Habitat dependent on geothermally-altered atmosphere overlays all types (warm air, frost-free)				

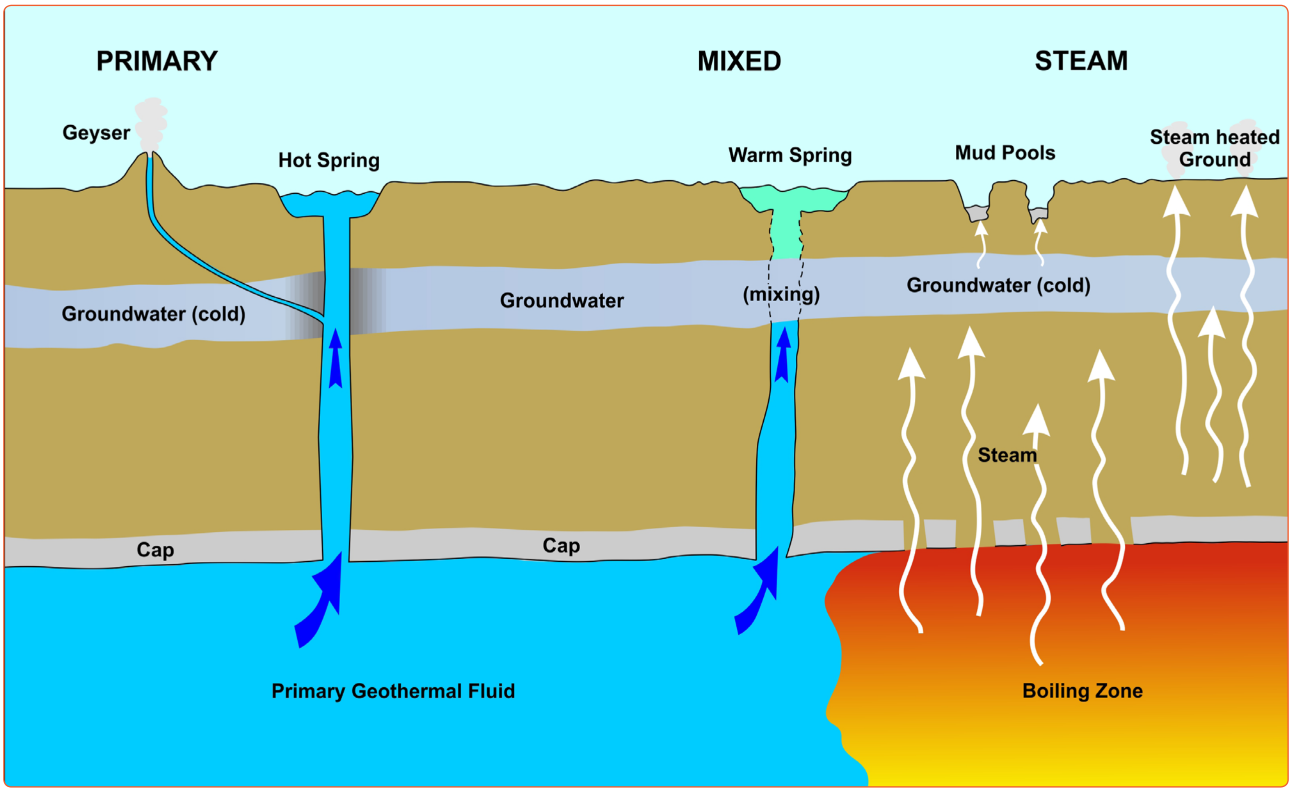


Figure 5 - Schematic of how surface features are generated.

Understanding the Value of Surface Features

The Regional Policy Statement (RPS) has high level objectives and policies that provide for the sustainable management of the geothermal resource. It also categorises geothermal systems, according to their values and use. The Rotorua System is classified as Group 2, where surface feature values override extractive values.

The RPS uses criteria[1] to assess the values of surface geothermal features . There are two sets of criteria, one for ecological values of geothermal vegetation, and the other for the geophysical values of features themselves. The criteria use three groups of values: Natural Science, Aesthetic and Associative. The criteria are factors to be considered and evaluated in order to reach an overall judgement as to the significance of any given feature(s)

The natural science factors cover how representative or distinctive a feature may be, along with its diversity or rareness. Also included are the resilience or vulnerability of the feature to change.

The aesthetic values are related to the perception and/or appreciation of the values or principles the community would associate with a surface feature, via how memorable or natural the feature appears.

The associative values examine the extent to which a geothermal feature is valued for its historical, recreational, educational or scientific values and the extent to which a geothermal feature is clearly special or widely valued by tangata whenua by reason of traditional values.

It is recognised that there are multiple values associated with the surface features however, different people will value the surface features in different ways.

1. For more information about the criteria see Appendix F of the Regional Policy Statement – Table 18 Criteria for assessing matters of national importance.
https://cdn.boprc.govt.nz/media/782167/operative-rps-1-october-2014-incorporating-change-3-appendix-f.pdf

Figure 6 - Map showing the location of the monitored surface features and the extent of the surface features.

Geothermal Vegetation and Habitats

Geothermally-influenced landscapes are dynamic ecosystems. The heat and soil chemistry of geothermally-active soils influence vegetation composition and structure. The dominance of geothermal kānuka, mānuka, and mingimingi within areas of heated soils are examples of species that have adapted to geothermal environments. Geothermal habitats are rare ecosystem types in New Zealand.

Geothermal ecosystems also provide habitats for threatened species and represent areas of high biodiversity value. Stream sides, heated ground, and hydrothermally altered ground, which are all found within the Rotorua system, are classified as 'Critically Endangered' ecosystem types. The geothermal habitats in Rotorua comprise approximately 30 % of geothermal vegetation in the entire Bay of Plenty Region.

Land use effects on surface features and ecosystems

Geothermal surface features and ecosystems can all be threatened by urban development, tracking and earthworks, vegetation clearance, structures, grazing and rubbish disposal. In some cases, surface features are infilled to create useable ground.

The process of urbanisation and land utilisation can also influence natural processes through redirection of heat flow (steam and gas) due to asphalting of road surfaces, building over warm ground and the redirection of runoff into geothermal features or collapse holes.

Human settlement has reduced the area and function of geothermal ecosystems and they are now recognised as being high priority for protection.

PART 2

Management, Use & Development

Historical Use and Development

Shortly after arrival on the Bay of Plenty coast Te Arawa people started to explore inland. The explorer Ihenga discovered the Rotorua lakes area and soon after people settled on the southern shores of Lake Rotorua. The abundant geothermal resources have been valued and used for hundreds of years. Māori consider geothermal a taonga (treasure), being used for cooking, bathing, heating, ceremonial use and healing for generations.

The geysers, flowing springs and other thermal features attracted visitors to the Rotorua area and tourism developed. The New Zealand government leased land from Ngati Whakaue in the 1880's to establish the town of Rotorua as a European style spa resort for tourists visiting the 'hot lakes'. The spring flows started to be manipulated and modified to provide for bathing and spa development.

Demand grew during the 1930's and 40's with tourism, farming and forestry post the second world war seeing bore numbers rise sharply in the late 1950's, declining to a steadier growth in the early 1970's.

Population growth, power shortages and first oil shock led to rapid, unregulated, demand growth in the late 1970's, and the decline of surface geothermal activity began. Fluid outflows were severely reduced, and many flowing springs and geysers stopped playing. Features like Te Horu, Korotiotio and the springs Tarewa and Waiariki Parekaumoana stopped overflowing. Geysers like Waikite, Wairoa, Papakura and Pareia ceased to erupt. It became very apparent development was destroying the geothermal surface features of Rotorua.

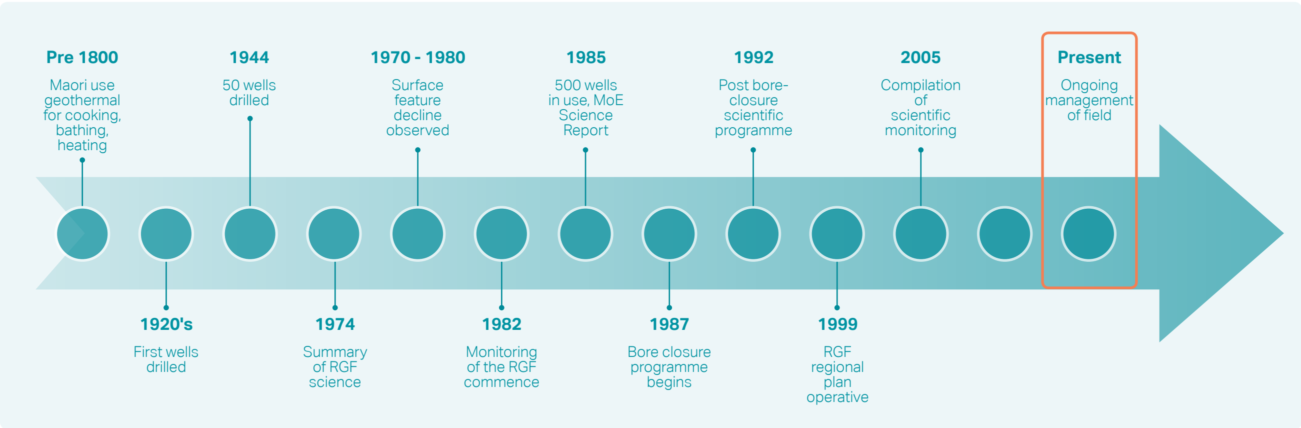


Figure 7 - Rotorua Geothermal Field Timeline.

Government Response

In 1980 the Minister of Energy and the Rotorua District Council announced guidelines for better efficiency and use of geothermal energy. This included no new bores with 1.5 km of Whakarewarewa. The Rotorua Monitoring Programme (RMP) was initiated in 1982 to support a management plan for the Rotorua system. Many issues were identified around gross inefficiencies and poor licensing.

By the mid-1980s, the RMP had quantified fluid extraction at over 30,000 tonnes per day. Also quantified was dramatic decreases in surface activity, including a 30% decrease in heat flow. Chemical studies confirmed the hot springs and bores used the same geothermal aquifer. The bore draw-off was causing a long-term drop in pressure, and wells closest to Whakarewarewa and Kuirau-Ohinemutu had a larger impact.

Action was needed to protect and preserve the Rotorua system. A Government enforced bore closure programme began around 1986; introducing a total ban on geothermal fluid extraction within a 1.5 km radius of Pohutu Geyser. This change resulted in an estimated 60% reduction in withdrawal of geothermal fluids. The number of shallow bores reduced from about 370 to 140.

Figure 8 - Total withdrawal from the geothermal system over time.

Current Management of the System

New Zealand's geothermal systems are now managed under the Resource Management Act 1991. Under the Act the Regional Council has responsibility for:

1. Allocation of geothermal energy and geothermal fluid and discharges to land, air and water
2. Protection of the surface features
3. Protection of people from geothermal hazards.

There are several relevant regional planning documents that guide management of the geothermal resource, including the Bay of Plenty Regional Policy Statement and regional plans.

The Rotorua Regional Geothermal Plan largely carried over the management regime bought in by the Government. Its purpose is to promote the integrated and sustainable management of the Rotorua geothermal resource. Under the plan the use and discharge of geothermal fluid requires a regional resource consent, unless it is a traditional take for the communal benefit of tangata whenua. Key policies are:

- an allocation limit of 4400 tonnes per day net mass abstraction from the system (i.e. loss to the system)
- Prohibited activity status for takes of geothermal water within 1.5km radius of Pohutu Geyser (i.e. the exclusion zone)
- Requirement for reinjection of geothermal water to source.

There are also policies for the protection of surface features, and the Rotorua District Plan (administered by Rotorua Lakes Council) includes rules for the protection of geothermal surface features and mitigation of hazards.

Current Uses and Values of the Geothermal System

The Rotorua system has a wide range of values. The unique surface features have significant cultural, ecological and landscape values and are a major attraction for tourism in Rotorua. In 2016/17 tourism in Rotorua was a $799 million per annum industry, and indirectly provides about 18% of employment. The continuation of the natural surface activity is vital for Rotorua tourism, a significant sector of the Rotorua economy.

Geothermal fluid is directly used for bathing and wellness, including commercial properties and private use. Space and water heating accounts for a significant proportion of the use, including commercial properties, the Rotorua Hospital and municipal facilities. Over 400 homes are heated by geothermal energy in Rotorua. There is currently no geothermal electricity generation or industrial direct heat use.

There are 130 consents for the take and use of geothermal water and energy in Rotorua. Many takes reinject fluid, mitigating depletion of the resource. There are also about forty down hole heat exchangers. Some still discharge waste geothermal water that has been bathed in to ground, lake, streams or district council storm water or sewer systems. Most consent applications received by BOPRC are for renewals (the consent timeframes being a maximum of 10 years).

Individual consumption varies from 2-600 tonnes per day. Most takes are under 200 tonnes per day, and 33% of consent holders account for 80% of total consented take. Commercial use accounts for about 85% of the total volume allocated.

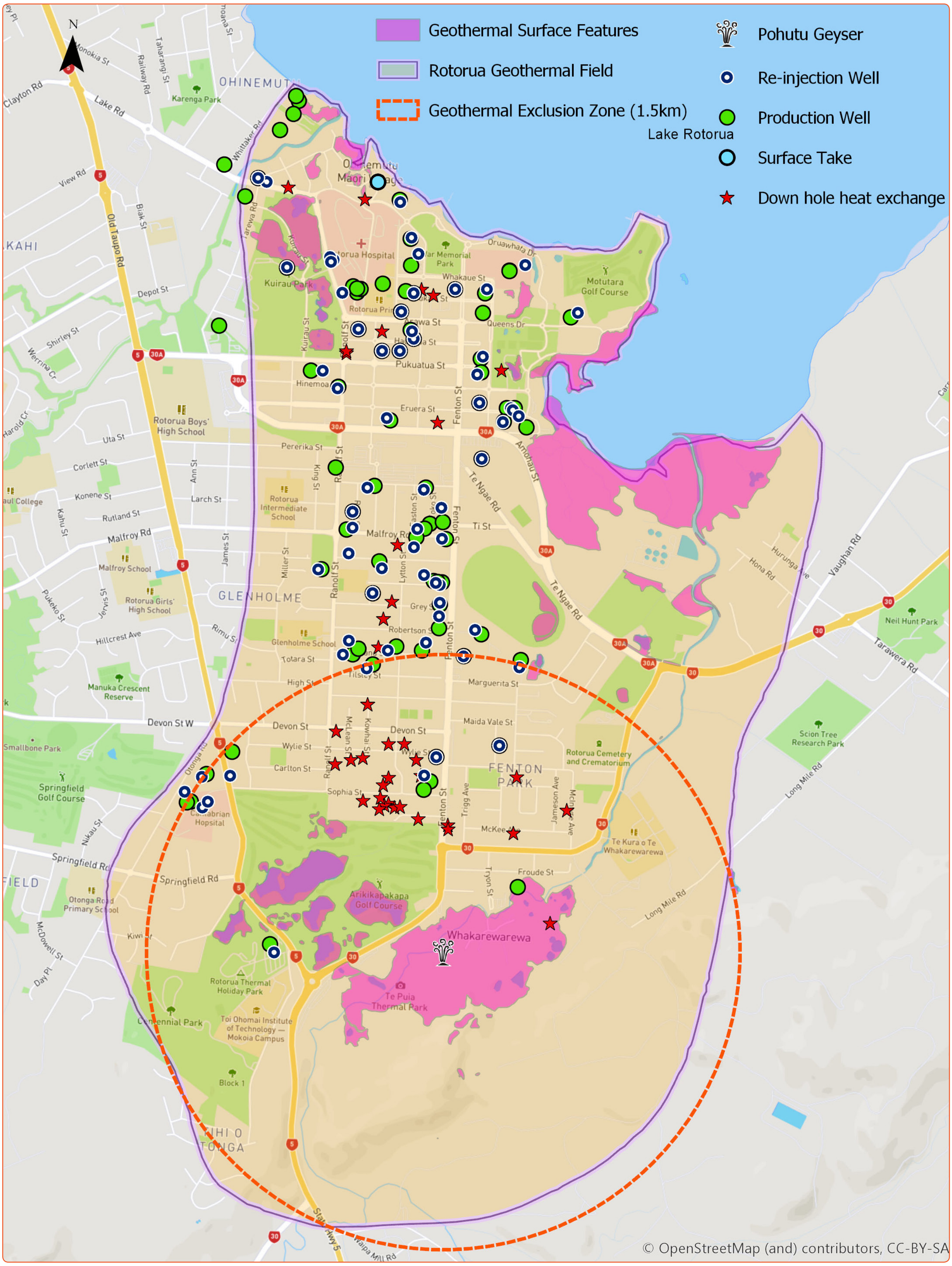


Figure 9 - Map of consented bores across the Rotorua geothermal field.

Table 2 - Summary of Geothermal Usage in the Rotorua Geothermal System.

	2005	2018
Total Withdrawal	9,700 tonnes / day	9,045 tonnes / day
Net Withdrawal		3,449 tonnes / day
Percentage of production volume from Domestic withdrawal	22%	16%
Percentage of production volume from Commercial withdrawal	78%	84%
Number of production bores	98	76
Number of down hole heat exchangers	42	38
Percentage wells Domestic	51%	41%
Percentage wells Commercial	49%	41%
Percentage wells mixed use	-	18%
Reinjection		~65% of Total withdrawal
Surface water disposal (soakage)		~1.3% of Total withdrawal

PART 3

Current State and Trends

To quantify the recovery and state of the Rotorua geothermal system the Regional Council in partnership with Crown Research Institutes (GNS, NIWA) and Universities monitor resource consents, the geothermal aquifer, groundwater, surface features, heat flow, fluids and gases. The data is used to assess the management of the geothermal field, monitor the sustainability of current resource use, inform resource management decision making and help develop effective models for long term resource management.

Unique in the world, management regimes introduced in the 1980-90 period and carried over into the Regional Plan have resulted in substantial recovery of the Rotorua Geothermal System. The bore hole data shows sustained aquifer recovery, as does the surface feature monitoring. However, some of the recovery trends in the surface feature data are inconsistent and we don't know why.

Monitoring the surface features has recorded several significant recoveries. In the north, Kuirau Park and Ohinemutu, the recovery has been very clear. Sinter lined basins that were dry in the early 1980s are now discharging fluids that are chemically like those observed prior to spring failure. At Whakarewarewa the recovery has been mixed.

The shallow aquifer feeding the bores has shown a positive and sustained recovery post the bore closure. Monitoring has also shown a slight chemical temperature increase. This indicates stability of the deeper system that feeds into the shallow, exploited, portion of the system.

Figure 10 - Bore Sampling.

Land use consents are required for the construction of geothermal bores, the conditions of which include the requirements to record, or measure:

- Drilled depth
- A log showing depths of geological strata intercepted by the well
- A temperature profile
- Wellhead pressure
- Depth to water level
- A calorimeter test
- Chemical analysis of discharged fluids
- Volume of fluid being taken

Monitoring Wells and Aquifer Recovery

Two sets of monitoring bores were established in 1982. The M series are drilled into the geothermal aquifer (60-244 m) to gather data including temperature profiles. The M series bores are used to assess the effect of the bore closures and post closure production on the geothermal aquifer. The shallow G series are used to understand the shallow groundwater aquifer that overlies the geothermal one.

Aquifer pressures are reported as water levels. Falling water levels reflect exploitation while rising trends show recovery.

This network of monitoring bores was established in 1982, and records aquifer pressures and temperatures. Some of these bores have failed and replacement bores have been drilled. There are nine bores currently monitored, five in the M series and four in the G.

Figure 11 - Photo of a M series bore.

The data from these monitoring wells is supplemented with data from consented bores in the shallow aquifer.

Data from the M series (Figure 12) clearly show:

1. The exploitation period up to mid-1986 when fluid was being extracted, there are strong seasonal trends and a consistent declining winter low.
2. The closure phase from 1986 to 1992. The immediate system recovery is clear with water levels rising over a metre in the first year. Note recovery of some surface feature and springs was also observed at this time.
3. The post-closure phase after 1992, showing a mix of equilibrium, continued aquifer and surface feature recovery. An overall increase in water levels of 2-2.5 metres, though with seasonal trends and differences related to other factors such as utilisation, geology and usage.

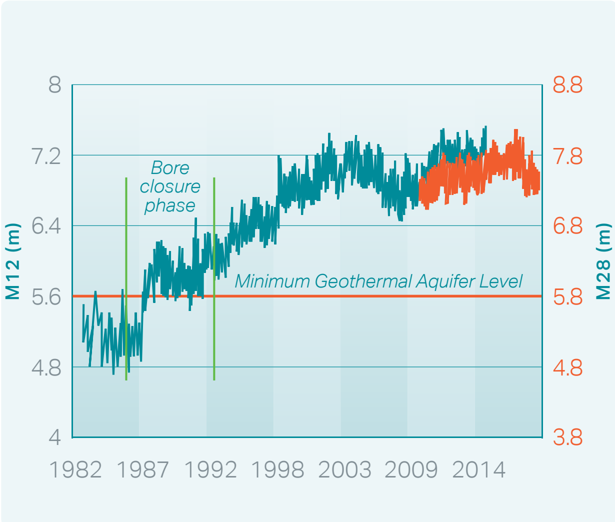


Figure 12 - Changes in water levels over time in the M12 (green line) and M28 (orange line) bores showing an overall rise in water level.

The data obtained before the bore closure show strong seasonal cycles, with lows in the winter period and highs in summer. The winter lows also showed a consistent declining trend.

Immediately post bore closure the geothermal aquifer across the system started to show a response, the water levels rose in all the monitor bores. There is variability in the bore responses, reflecting the geology, permeability, drilled depth and the aquifer tapped. The water levels rose over a meter in the first year. Coincident with this recovery in the drilled aquifer, responses were also noted in many of the monitored springs.

Over the next 15 to 20 years trends consistent with recovery and equilibrium have continued to be recorded. To date rises of the order 2-2.5 meters have been recorded. However, both short and long-term behaviour has varied during this time. These variations reflect the complex interactions between factors like usage, seasonal changes, the geology, drilled permeability and reinjection.

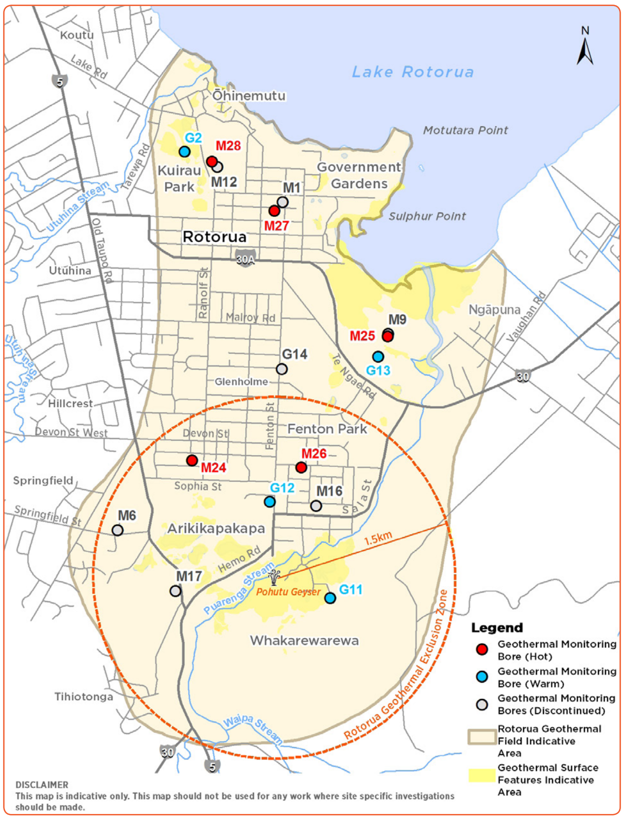


Figure 13 - Monitoring Bores.

Surface Feature Monitoring and Recovery

Forty surface features have been monitored since 1989. Monitoring includes water level/flows, temperatures, physical aspects and some chemistry.

As the geothermal aquifer started to show rising levels, recovery was also noted in some surface features. By 2000, many surface geothermal features in the Rotorua system were showing significant recovery. In the north and north-west the recovery has been striking and sometimes spectacular. Some surface features such as those in the Kuirau Park-Ohinemutu area have recovered to levels last seen in the 1950's.

In the southern part of the Rotorua system, Whakarewarewa (Te Puia-Whakarewarewa Village) contains numerous geothermal features of all types, including the only active geysers in Rotorua. In this area the response of the surface features to the closures has been very mixed. Some features have shown good recovery, in October 2013 Papakura Geyser restarted overflowing and erupting, being the first geyser feature to start to recover.

Chemistry

The chemistry of the bore water and surface features provide important information on hydrological processes in Rotorua. Studies of the chemical composition of the hot springs and geothermal bores (wells) confirm that they are fed from the same geothermal aquifer.

Fluid flows across the field can be inferred from changing chemical characteristics of the water and gases across the field. Chloride and boron levels, indicative of the presence of primary geothermal fluid from depth, decrease significantly east to west, from Ngapuna to Kuirau Park. Bicarbonate, which arises from water–rock interaction at shallower depths increases in the same direction. Condensation of steam and oxidation of hydrogen sulphide by groundwater results in elevated sulphate and acidic fluids at very shallow levels in many parts of the field.

Chemical changes in the monitoring bores vary over time, but most trends indicate field recovery:

- Government Gardens and the west show positive trends in sulphate and bicarbonate, with chloride trends inconsistent.
- In the north, Kuirau Park monitoring now matches data from the early 1960's with consistently high chloride and temperature readings since 2003. This part of the field may be fully recovered.
- Inconsistent chemical data from Whakarewarewa springs indicate recovery that may still be underway. Large increases in reservoir pressures have occurred, but only a few springs have reactivated.

Temperature

Data from geothermal bore holes is used to create temperature contour maps. At 180m above sea level (90m depth) the temperatures range from below 100 to 170 °C. Self-discharging bores are likely in up flow zones with temperatures of 150-200 °C.

Temperature data has defined three up flow zones: Ngapuna, Whakarewarewa and Kuirau Park, at about 100m depth, and an out-flow zone to Sulphur Bay and Lake Rotorua.

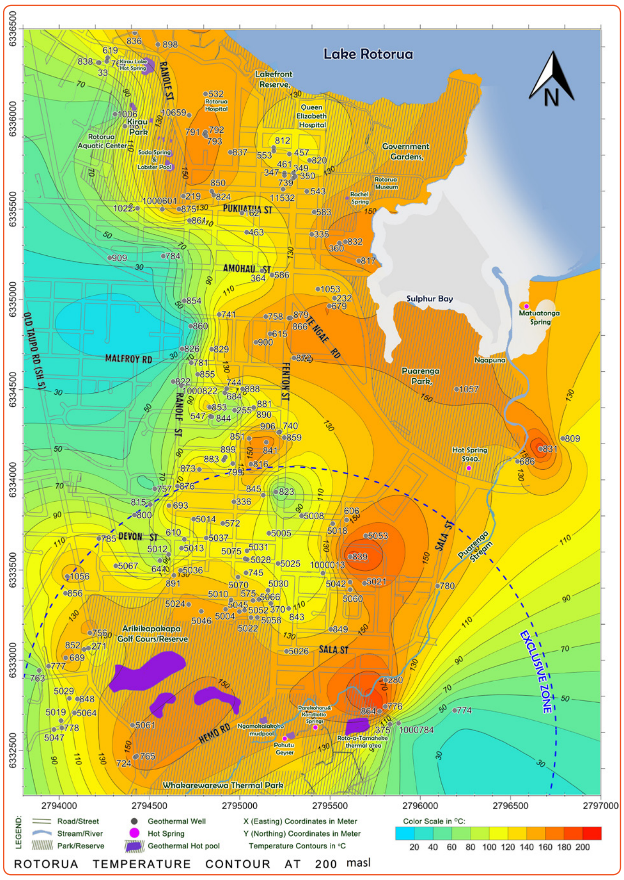


Figure 14 - Rotorua temperature contours at 200 metres above sea level (after Scott et. al. 2016).

Surface Heat Flow

Heat flow in geothermal systems is the amount of heat energy in megawatts (MW) transferred between the ground, or surface water, and the atmosphere. Changes in heat flow indicate changes in the system. Heat flow can be inferred from chemical changes in the geothermal fluid (e.g. chloride concentrations) or measured directly using a calorimeter or steam venture.

Heat flow surveys at Whakarewarewa show a reduction between 1967 and 1984 (229 – 158 MW, -31%) and a further reduction of 24% from a survey in 2010 attributable to loss of surface flow. A 2018 survey has shown some recovery however, heat transfer is now at around 80% of that in 1967, again indicating possible ongoing recovery at Whakarewarewa.

Thermal InfraRed (IR)

In 2014 a thermal IR survey was flown over Rotorua, to allow comparison with data from the 1990 survey. This data is used to compare geothermal surface features between the two dates. The Ngapuna, Ohinemutu, Kuirau, Arikikapakapa areas are calculated to have similar geothermal surface areas, while Sulphur Flats and Whakarewarewa show a decrease in the area of geothermal activity between surveys. This result is consistent with variation seen in the monitoring of surface features.

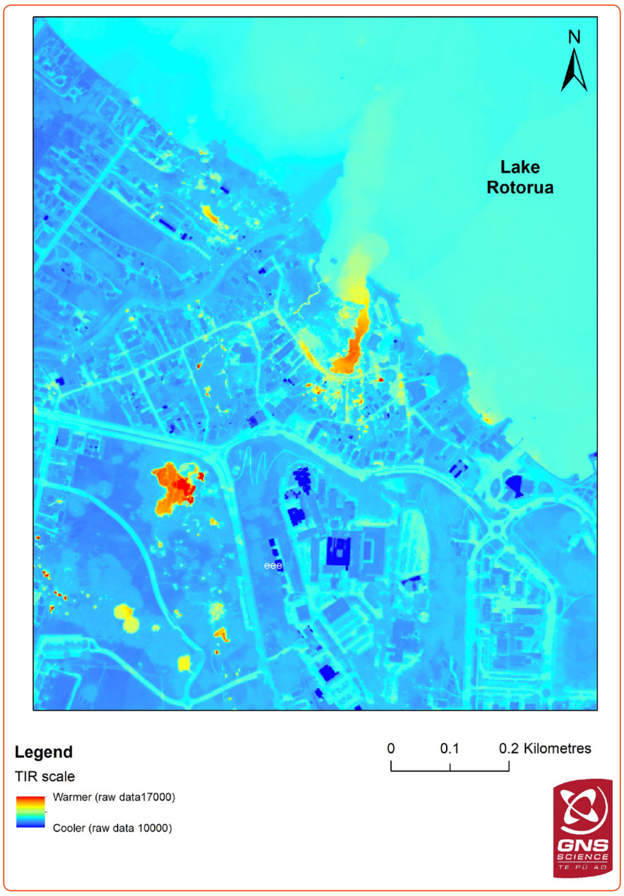


Figure 15 - Thermal IR image Ohinemutu (after Reeves et. al. 2014).

Hydrothermal Disturbances

The frequency of disturbances and hydrothermal eruptions has been declining having peaked in the 1970's – 1980's. This is attributed to over exploitation of the geothermal resource. They have been rare since early 2000. This indicates positive results from a management system that requires reinjection.

The last significant events were in 2000 and 2001 at Kuirau Park. The higher aquifer water levels observed since around 2000 in the M series monitor bores is consistent with the system being in a more stable state.

Hazards

Geothermal hazards include high temperature fluids and steam, gas, ground collapse and hydrothermal eruptions. In general protection from these hazards can be achieved by controlling the development activities that are allowable in areas of known risk and restricting access.

The formation of collapse holes is a hazard in Rotorua. Weakening of the ground can occur by steam and/or acid condensate, resulting in the formation of a cavity that can move towards the surface and collapse. This is usually restricted to areas of higher heat flow where steam is present such that restrictions on development help to manage these risks.

Hydrothermal eruptions can occur in any part of a high-temperature geothermal system, when there is an abundance of steam present. They are difficult to predict and vary greatly in size. Small hydrothermal eruptions are most likely to occur in places where the geothermal heat flow is very high, where there are boiling springs or high steam flows.

Minor events originate at depths of a metre or so below ground and discharge mostly water, mud and blocks to few tens of metres from the vent.

Major explosions, like those preserved in the geological record, may be caused by nearby volcanic activity related to events like large lake level changes, or triggered by large earthquakes. The geological record suggests these major events are very infrequent, occurring a few times in the lifetime of a geothermal field.

How do steam eruptions occur?

Imagine an electric jug on the bench at home. There will be water and steam present as it boils. The lower the water level, the larger proportion of steam present. As the jug is filled the proportion of steam decreases. The same happens in the geothermal system. As the discharge via bores draws down the water level, more steam is produced in the shallow geothermal aquifer and the likelihood of eruptions increases.

The number of these events has declined significantly since the bore closures, as the level in the geothermal aquifer has risen (i.e. the jug is getting filled).

Gas

The Rotorua system is famous for its distinctive rotten egg odour, due to hydrogen sulphide gas. Hydrogen sulphide is dissolved in the geothermal fluids along with other gases such as carbon dioxide. These gases may remain in solution mixed with other fluids at the surface, or release through the soils. Highest gas flows occur where steam feed surface activity is strongest, such as the upflow zones.

The gas can be found in concentrations above the lethal thresholds in contained or enclosed locations but dissipates quickly to safe levels in open spaces. Health studies confirm that respiratory issues are similar in Rotorua to the rest of New Zealand, indicating that with safety processes in place the gas hazard is minimal.

Earthquake Activity

The Rotorua Caldera (basin) is a known earthquake hot spot, as are several other geothermal systems in the Taupō Volcanic Zone. Quality earthquake data has been available since around 1990 and over 800 shallow earthquakes have been located, ranging in size from magnitude1.4 to 3.7. The events tend to cluster under the northern portion of the city, with a secondary cluster to the south. There has been a decline in the number events since 2014.

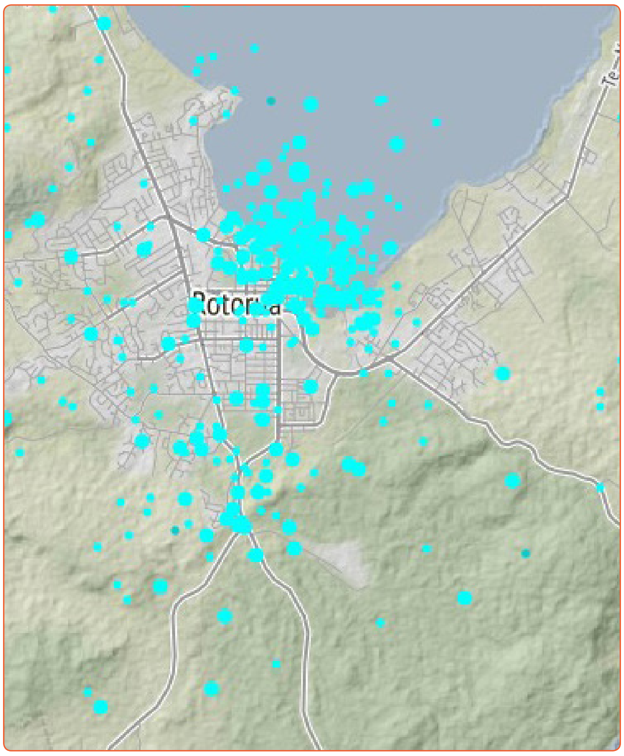


Figure 16 - Map showing location of recorded earthquakes since 2000.

PART 4

Modelling and Future

Modelling

Modelling is a way of describing the physical features of a geothermal system and predicting the effects of uses. Understanding the interactions between the solid, liquid and gaseous elements of a geothermal field is highly complex. To assist in this understanding and to make predictions of the future behaviour of the Rotorua Geothermal System, computer models have been built that simulate the underground processes. There are two types of model:

- A 'conceptual model' is a representation of a system. The model helps people know, understand, or simulate the geothermal system.
- A 'reservoir' model is a mathematical representation incorporating all the 'characteristics' of the reservoir.

The conceptual model of the Rotorua system was first produced in 1985, with several subsequent revisions. It includes key features like chemistry, fluid flow, geology and energy. The conceptual model is supported by real life data (measured data).

The computational or reservoir model is resolved mathematically by a geothermal simulator or computer program. This calculates the likely pressures, temperatures and flows in a geothermal system based on knowledge of how the system works (i.e. the conceptual understanding). The simulator solves mathematical equations that describe how fluid and heat moves through porous rocks. The output is calibrated by comparing with measured real life data.

The Regional Council uses a reservoir models to help manage the Rotorua Geothermal System. The key uses of modelling are to test the validity of real data and model outputs against management policies along with testing scenarios. In scenario-based testing trends can be explored and examined. It is possible to do 'what if' analysis.

Comparing the outputs of the current model against real data has shown this model to be a good predictor of system response to change. Figure 17 shows the measured real life data versus the modelled data.

The Regional Council's model is currently undergoing a further check and revisions to inform the Regional Plan Review.

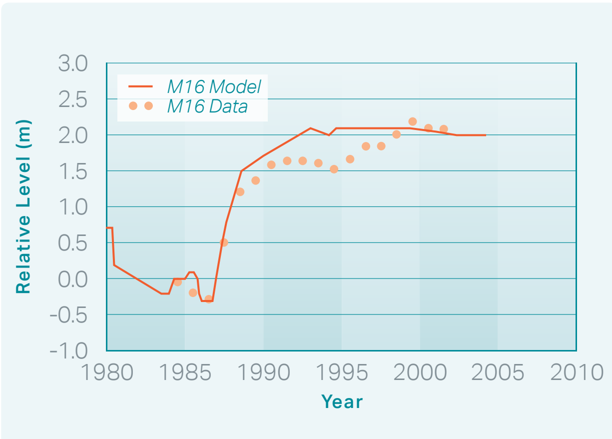


Figure 17 - Measured (real life data) versus model results for Bore M16.

Gaps / Future Monitoring

The Regional Council has a robust, scientific consenting and monitoring regime that informs models and the fundamental understanding of the Rotorua system. However, there are gaps and shortfalls. Some that are identified include:

- Surface feature monitoring could be improved both through inclusion of more areas, such as Ngapuna, and by more regular monitoring to investigate shorter term trends.
- Groundwater can indicate reduced/increased pressures before surface features are impacted. Monitoring data on trends in the shallow vs deep aquifers could improve management planning.
- Geothermal resources have been an integral part of Māori culture in Rotorua. Māori have traditional knowledge of changes and events. Little is known of this and how this may inform management of the resource.
- The Regional Council has been actively funding deep (>250m) geothermal research using Magnetotallotelluric surveys in the region to better understand the feed zones. There is currently no deep drill hole to quantify these areas.

The Regional Council is also testing ways of measuring the actual use of the geothermal fluid, as opposed to what is consented. Because the fluid is hot, sometimes under pressure and contains gases this is not always easy. The Regional Council has funded development of technology to achieve this and better quantify the actual use.

Summary

RESOURCE

STATE:

There has been resource recovery and now there is a mix of preservation and resource exploitation.

TREND:

There has been an increase in geothermal aquifer levels across the system since management measures were introduced, although this has now stabilised. Reinjection has been shown to be a key management activity.

CHEMISTRY

STATE:

Increased chloride and boron in monitoring bores, indicating recovering pressures in the primary geothermal fluid.

TREND:

Areas to the north and north west show improved recovery compared to the South, Whakarewarewa may still be recovering.

SURFACE HEATFLOW

STATE:

Surveys show heat flow is around 80% of that in 1967.

TREND:

Several heat flow surveys showed a continued decline from 1967 to 2010, with a 2018 survey recording the first increase. Surface surveys show variable recovery, with north and north western areas recovering better than the south.

SURFACE FEATURES

STATE:

Credible recovery of surface features has occurred across the system. This is more notable in the north and north west, with more mixed recovery in the south. For example, Korotiotio shows essentially no recovery while Papakura Geyser recommenced overflow in 2013.

TREND:

Recovery trends are positive across with the system, however mixed results are also present. Surface feature recovery trends with chemistry recovery may be lagging in some features in the Whakarewarewa area.

RESOURCE CONSENTS

STATE:

The current level of consented exploitation of the aquifer appears to have produced an equilibrium between use of the resource and recovery of many surface features.

TREND:

The limits to exploitation within the exclusion zone, and allowing extraction with reinjection to replenish the aquifer, has created a recovery trend since the 1980's that is reflected in both surface features and the underlying geothermal aquifers.

Glossary

Acidic: relating to fluids with pH less than 7 (acid).

Alkaline: relating to fluids with pH greater than 7 (alkali) and igneous rocks with high concentrations of the alkali metals lithium, potassium, sodium, rubidium, caesium and/or radium.

Ash: fine particles of pulverized rock (tephra) erupted from the vent of a volcano. Particles smaller than 2 mm in diameter are termed as ash.

Caldera: a volcanic depression formed by the collapse of the ground above a magma chamber, which empties during very large volcanic eruptions. The diameter of a caldera many be times larger than the size of the individual vents

Carbon dioxide: a gas composed of carbon and oxygen (CO2) and a key greenhouse gas; the dissolved form is bicarbonate (HCO3-). A common volcanic gas.

Crater: a commonly circular depression formed by either explosion or collapse at a volcanic vent, from which volcanic material is erupted.

Fault: a major fracture or dislocation along which the crust has moved.

Fracture: a brittle crack in the crust.

Geothermal system: the natural transfer of heat within a confined volume of the Earth's crust where heat is transported from a 'heat source' to a 'heat sink', usually the ground surface.

Geology: the study of the composition, structure and origin of the solid Earth; sub-disciplines include geochronology, engineering geology, mineralogy, petrology, palaeontology and stratigraphy.

Geothermal: relating to natural heat within the crust and heat from hot groundwater or steam used for power generation.

Geyser: an eruption of hot water and steam from a hydrothermal system. It is usually of cyclic occurrence and ejects only small amounts of solid material. The ejection mechanism is volume change due to boiling, as opposed to ejection of water because of artesian pressure alone.

Groundwater: subsurface water contained in pores and fissures in rock beneath soil, most of which is beneath the water table.

Hot springs: a surface feature of a geothermal system, where warm or hot water flows out of the ground.

Hydrogen sulphide: a poisonous, strongly odorous gas composed of hydrogen and sulphur (H2S). A common volcanic gas.

Hydrothermal: relating to naturally occurring hot water—often referred to as 'thermal' at tourist locations—whose minimum temperature is higher than the ambient mean annual temperature.

Hydrothermal activity: manifestations seen at the surface of geothermal systems. Hydrothermal activity may include hydrothermal eruptions, fumaroles, gas/steam emissions, steaming ground, geysers, hot springs and streams, and hot pools (including mud pools).

Hydrothermal eruption: an eruption ejecting steam and some solid material. Energy is derived only from a convecting hydrothermal system, not magma.

Lava: molten rock that has reached the Earth's surface and been thrown out of or has flowed from a volcano or volcanic vent. Molten rock that is still underground is called magma.

Lava dome: a steep-sided pile of viscous (i.e. sticky) lava at a volcanic vent. The surface is often rough and blocky because of fragmentation of the cooler outer crust during growth of the dome. Lava domes can collapse and cause block and ash flows.

Magma: molten or partly molten rock beneath the surface of the earth. Magma that reaches the surface erupts as lava or pyroclasts from a volcano.

Magnitude: A measure of the energy released by an earthquake at its source. Magnitude is commonly determined from the shaking recorded on a seismograph. Each unit of magnitude on the scale represents a substantial increase in energy, for example a magnitude 5 releases 30 times more energy than a magnitude 4.

Magnetotelluric survey: An electromagnetic surveying method used to map subsurface resistivity variations by measuring naturally occurring electric and magnetic fields on the seabed or the Earth's surface.

Pyroclastic flow: is a fast-moving current of hot gas and volcanic matter that moves away from a volcano about 100 km/h on average but is capable of reaching speeds up to 700 km/h.

Reservoir: a porous volume within a rock formation containing fluids.

Resistivity: How strongly a material opposes the flow of an electric current.

Steam eruption: usually small eruptions consisting mostly of steam. Rocks and ash might also be erupted, but no fresh magma is deposited. Steam eruptions include hydrothermal eruptions.

Taupo Volcanic Zone: the c. 100 kilometre wide by c. 350 kilometre long volcanic region of central North Island extending north from Ruapehu volcano to beyond White Island volcano; the 'older TVZ' was active from c. 2 Ma to 340 ka, and the 'younger TVZ' has been active since c. 340 ka.

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