Waikato Regional Council Technical Report 2022/09

# State of the Environment report on the Waikato regional geothermal resource, 2022

www.waikatoregion.govt.nz
ISSN 2230-4363 (Online)

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October 2022

Document #: 23514944

Peer reviewed by:
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Approved for release by:
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# Acknowledgement

The author gratefully acknowledges the support and guidance of her Waikato Regional Council science colleagues, particularly Mike Scarsbrook, Thomas Wilding, Michelle Begbie and Jim McLeod.  In addition, this work rests on the countless hours of investigation, monitoring, research, and reporting undertaken by Waikato Regional Council Environmental Monitoring team, contractors, and external geothermal researchers in New Zealand's Crown Research Institutions and universities.  This country's world-class geothermal scientific community's ethic of collegiality has enabled the provision of much useful data and information, debate, and consensus.

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# Abstract

The Waikato Region contains approximately 70 per cent of the nation's geothermal resources. Waikato Regional Council is responsible for sustainable management of the regional geothermal resource. Waikato Regional Council is required under Resource Management Act 1991 S35 to monitor, keep records, and report on the state of the environment, including the Regional Geothermal Resource.

For State of the Environment Reporting, this report provides an overview of the state and trends in the nature, extent, and condition of the regional geothermal resource, assessed against the DPSIR framework (Drivers, Pressures, State, Impact and Response model).

Degradation of the geothermal surface resource through large-scale destruction of surface features, and depletion of the geothermal resource by excessive extraction of the subsurface energy and fluid, have effectively ceased since the Resource Management Act 1991 was enacted and the Waikato Regional Policy Statement and Waikato Regional Plan developed, giving policies and rules that ensure sustainable management of geothermal resources. However, ongoing small-scale destruction of geothermal features through inappropriate land use activities continues as a result of land use intensification.

Ensuring that all uses of geothermal resources are sustainable is now more important than ever before as we face increased pressure to use geothermal resources for electricity generation and as intensification of land uses and subdivision encroach upon rare and vulnerable geothermal ecosystems.

Lack of funding for geothermal monitoring and research severely impairs our ability to identify and respond to the threats.

# Executive summary

Waikato Regional Council is responsible for sustainable management of the regional geothermal resource. For State of the Environment Reporting, this report provides an overview of the state and trends in the nature, extent, and condition of the regional geothermal resource, assessed against the DPSIR framework (Drivers, Pressures, State, Impact and Response model).

The Resource Management Act 1991 (RMA) s30 gives regional councils the control of:

- taking or use of geothermal energy and water,
- the quantity, level, and flow of geothermal water,
- discharges of contaminants into or onto land, air, or water and discharges of water into water.

RMA s30 also confers on regional councils the function of managing indigenous biological diversity.

The Waikato Region contains approximately 70% of the nation's geothermal resource, including most of the country's naturally rare and vulnerable geothermal ecosystems. Most of this geothermal activity is found within the Taupō Volcanic Zone, the band of volcanic and geothermal activity that stretches from Mt Ruapehu northwest to Whakaari (White Island) and beyond (See Figure 2).

The legend of Ngātoroirangi describes how geothermal energy arrived in New Zealand and gives the story of the relationship tangata whenua in geothermal areas have with the resource. Tangata whenua with particular interest in geothermal resources within the Waikato Region are people from Waikato-Tainui, Te Arawa, Ngāti Tūwharetoa, Ngāti Tahu, Ngāti Whaoa, Raukawa, Maniapoto, Hauraki and Tuaropaki.

Over the years until 2022, several factors have influenced Waikato Regional Council's understanding of geothermal resources and their management. We have learnt more about the uniqueness and fragility of geothermal features and ecosystems [Parkyn and Boothroyd, 2000; Duggan and Boothroyd, 2001; Duggan and Boothroyd, 2002; Stevens *et al.*, 2003; Wildland Consultants Ltd., 2004, 2006a, 2006b, 2007a, 2007b; Cody 2007; Keam *et al.*, 2005]. At the same time, society is becoming more aware of the value of biodiversity and is placing a greater value on rare ecosystems and their dependent organisms [Department of Conservation, 2000]. In addition, the tourism value of geothermal resources is becoming more important to the people of the region [APR Consultants, 1994; Bay of Plenty Regional Council, 1999; Chrzanowski, 1997; McDermott Fairgray *et al*, 1996; Luketina, 2002]. The adverse effects of some uses of geothermal resources are becoming better understood, and society is requiring that such effects not be placed as a burden on society, but as a cost for those who cause the effects. Sustainability of natural and physical resources is becoming more important and the issues surrounding sustainability are becoming better understood [UNCED, 1992].

# 1 State of the Environment reporting under the DPSIR framework

Regional Councils are required under RMA s35 to monitor, keep records and report on the state of the regional environment. Waikato Regional Council produced a comprehensive State of the Environment (SOE) report in 1998 (Waikato Regional Council, 1998) and since then has updated its reporting regularly through its website.

In 2019 the Parliamentary Commissioner for the Environment produced a report on the state of SOE monitoring in New Zealand, evaluated against the requirements of the Environmental Reporting Act 2015 (Parliamentary Commissioner for the Environment, 2019). One of the recommendations was the adoption of the internationally accepted 'Drivers, Pressures, State, Impact, Response' (DPSIR) framework for evaluating the state of the environment (See Figure 1).

Waikato Regional Council's Science section has adopted the DPSIR model for an updated SOE report in 2022, and it is under that model that this chapter evaluates the state of the Regional Geothermal Resource.

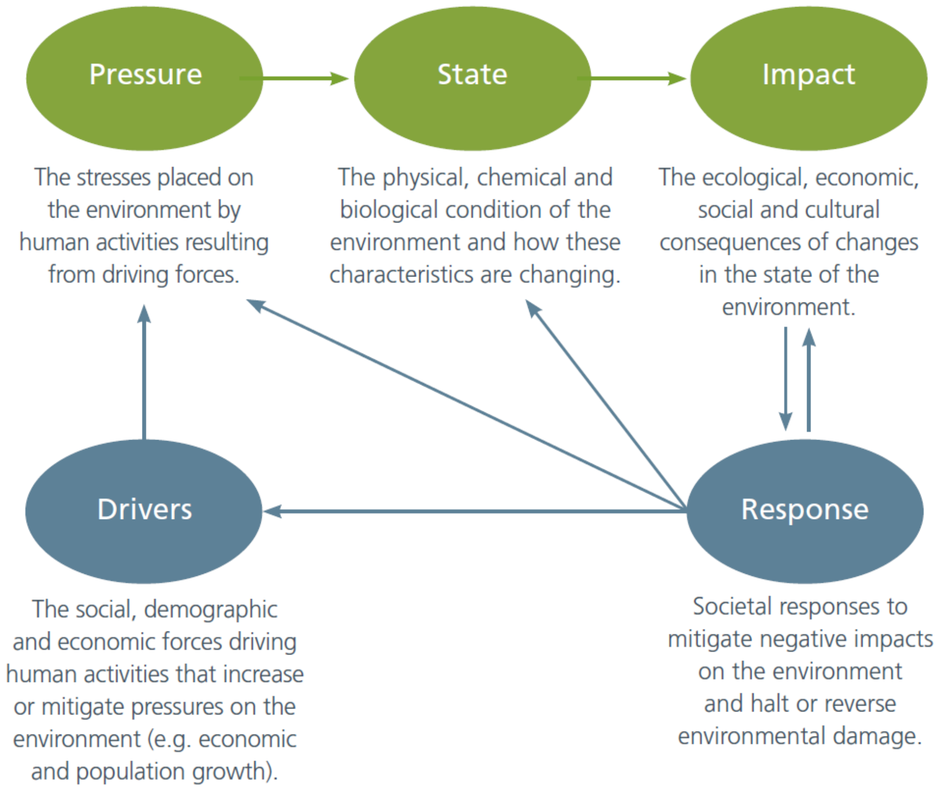


**Figure 1: The DPSIR reporting framework (from Parliamentary Commissioner for the Environment, 2019)**

# 2 Description of geothermal resources

## 2.1 Definitions

**Geothermal energy** is defined in RMA s2 as: "energy derived or derivable from and produced within the earth by natural heat phenomena; and includes all geothermal water".

Geothermal resources can be divided naturally into management units known as **geothermal systems**. The Waikato Regional Policy Statement defines a geothermal system as an individual body of geothermal energy (including geothermal water) not believed to have a fluid connection to any other in the upper few kilometres of the Earth's crust. At greater depths, it is accepted that there is a common heat source, and this is consistent with Māori understanding of the geothermal resource. In some cases, there is doubt over the near-surface hydrological separation between particular geothermal systems. A geothermal system may be indicated by geothermal surface features such as an isolated hot spring or set of hot springs, or a much larger set of features. Alternatively, there may be no visible expression at the surface.

All known geothermal systems in New Zealand are hydrothermal systems, i.e., they involve a circulating body of geothermal water that transports heat and minerals from depth to near the surface. Some of this water is discharged to the surface via geothermal features such as springs and fumaroles. There may be other, hidden geothermal systems that do not support hydrothermal circulation. These are known as Hot Dry Rock (HDR) systems. Overseas, attempts are being made to tap such systems by creating Enhanced Geothermal Systems (EGS), in which water is injected into the system via a well and recovered from another well once it is heated. As yet there are no large-scale electricity developments using HDR despite more than thirty years of research.

Hot Sedimentary Aquifers are a potential source of electricity. These occur in places where water confined within a porous rock matrix is heated by non-magmatic sources such as radioactive decay of uranium, as in Australia. There is as yet no electricity production from such sources.

Another potential source of geothermal energy involves drilling directly into near-surface magma. Again, this technology is in the experimental stage.

The volumetric extent of a geothermal system is taken to be the extent of the interconnected bodies of water heated within the earth by natural phenomena to a temperature of 30 degrees Celsius or more. The determination of the land surface boundaries of geothermal systems is difficult because within the earth the interconnected geothermal water bodies are irregularly located, and horizontal cross-sections at different depths can lie under different areas of land.

The Waikato Regional Plan defines and maps the system boundaries for all known high-temperature geothermal systems in the Waikato Region. Council policies and rules relating to use of geothermal resources apply within these boundaries, which are conservatively based on resistivity measurements to 500 and 1000 metres depth, drilling results, location of springs, geology, and all other available geochemical and geophysical data. (Risk 2000a, 2000b, 2003).

In recent years the geophysical prospecting technique of magneto-tellurics has enabled scientists to better understand the resistivity structure of the earth to depths of up to 10 kilometres, and therefore the deep structure and 3-dimensional boundaries of geothermal systems. While such data exists for many of the geothermal systems of the Waikato Region, the statutory regional boundaries have not been updated in the light of this data.

Based on the current understanding of the origins of geothermal systems, they can be divided into four types – **magmatic** systems**, active volcanic** systems, **ancient volcanic** systems and

**tectonic** systems. The heat from a **magmatic** system is believed to derive from a body of magma, or pluton, which has become completely or nearly disconnected from the magmatic core of the Earth and risen close to the surface of the Earth. There may be intrusions of fresh magma from time to time. In an **active volcanic** geothermal system, the heat source is active volcanic magma. **Ancient volcanic** systems contain a large body of heated fluid left over from a now-extinct volcano. T**ectonic** systems are associated with areas of above average temperature gradient and active faulting. Hot water may be confined to the fault, with no extensive reservoir of geothermal water associated with the system.

These four types can be divided into **high-** and **low- temperature** systems. Most magmatic and active volcanic systems are high-temperature systems, containing fluid hotter than 120 °C, but some of the older, waning ones are low-temperature, with fluid between 30 and 120 °C. All the ancient volcanic and tectonic systems are low-temperature systems.

Most high-temperature systems are **large** in extent. They each cover many square kilometres and extend to depths of several kilometres. They contain many cubic kilometres of heated rock and geothermal fluid with temperatures of up to 350 °C in the currently accessible upper few kilometres of the system.

Most low-temperature systems are **tectonic** systems that are **small** in extent. In addition to these tectonic systems, some ancient magmatic or volcanic systems have lost most of their heat and now only produce warm water and are considered to be small systems. Small systems contain small quantities of geothermal water that is generally lower in heat and mineral content. They have few surface features and in general, the surface features are less rare and less vulnerable than those found in the high temperature systems. These systems are nevertheless important culturally, and economically as sources of hot water for bathing. Small geothermal systems are scattered throughout the region, including the Taupō Volcanic Zone. They generally produce water of less than 100 °C and are small in area and volume of water discharged.

Fresh ground water in the Waikato Region normally has a temperature somewhere between 15 and 20 °C. Groundwater found with a temperature between 20 and 30 °C is likely to have a geothermal component and is of interest to geothermal scientists, although it does not fall within the Resource Management Act 1991 definition of geothermal water.

A large geothermal system may contain more than one **geothermal field**. A geothermal field is an area of separate upflow that may have surface features. For example, the Wairakei and Tauhara fields are supported by individual upflows on the Wairakei-Tauhara geothermal system (see Figure 3).

Geothermal **features** are defined as surface manifestations of geothermal processes or discharges, including steam-fed features, geothermal water-fed features, and remnant features such as hydrothermal eruption craters and ancient sinters.

They include hot or steaming ground, hot springs and pools, deposits of sinter, sulphur, and other minerals, mud pools, and fumaroles. A feature or **group** of features usually has a thermophilic (heat-loving), thermotolerant (heat-tolerant) or extremophilic (adapted to extremes of heat, pH or chemical concentration) ecosystem associated with it. A field may contain many groups of such features, or isolated individual features.

Geothermal features and ecosystems are important for several reasons. Geothermal features and ecosystems are rare, extremely fragile and many are impossible or almost impossible to restore once damaged. They buffer the biosphere from the high temperatures and toxic chemicals in geothermal discharges. As a geothermal discharge flows over sinter terraces, it cools and adds to the sinter, depositing other minerals in the process. Sinter deposition is understood to be in many, and possibly most, cases, mediated by thermophilic microorganisms (Gong et al., 2022). Thermally tolerant plants and micro-organisms living in the outflow extract further minerals. The reduced toxicity of the geothermal fluid discharge has enabled other plants, animals, and micro-organisms to evolve. Geothermal biota makes significant contributions to biological diversity, scientific understanding, scenery, and aesthetic enjoyment. Like geothermal systems, fields, and features, geothermally adapted plants, animals and micro-organisms also have intrinsic qualities.

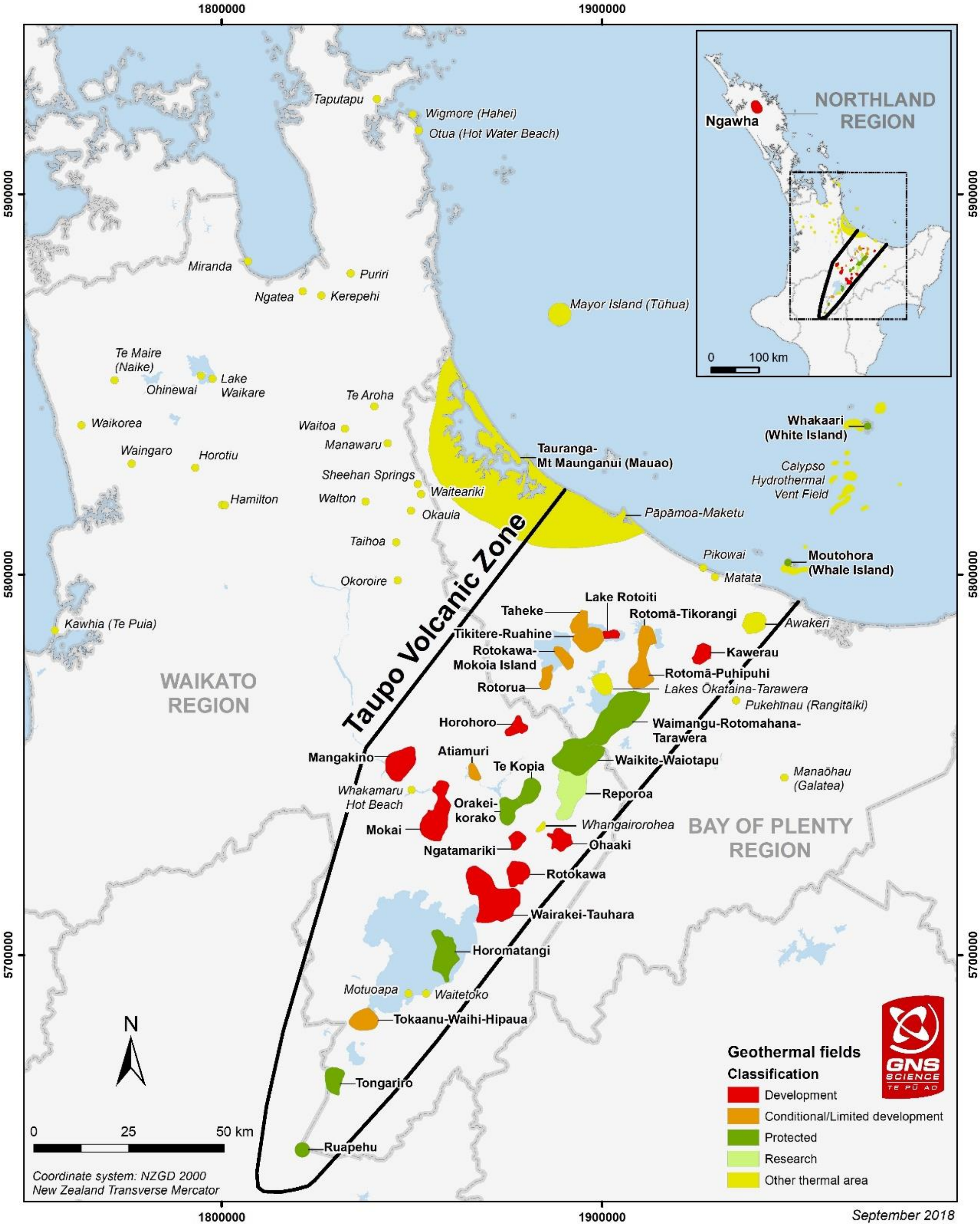


**Figure 2: Geothermal resources of the Waikato and Bay of Plenty Regions (map courtesy of GNS Science and New Zealand Geothermal Association)**

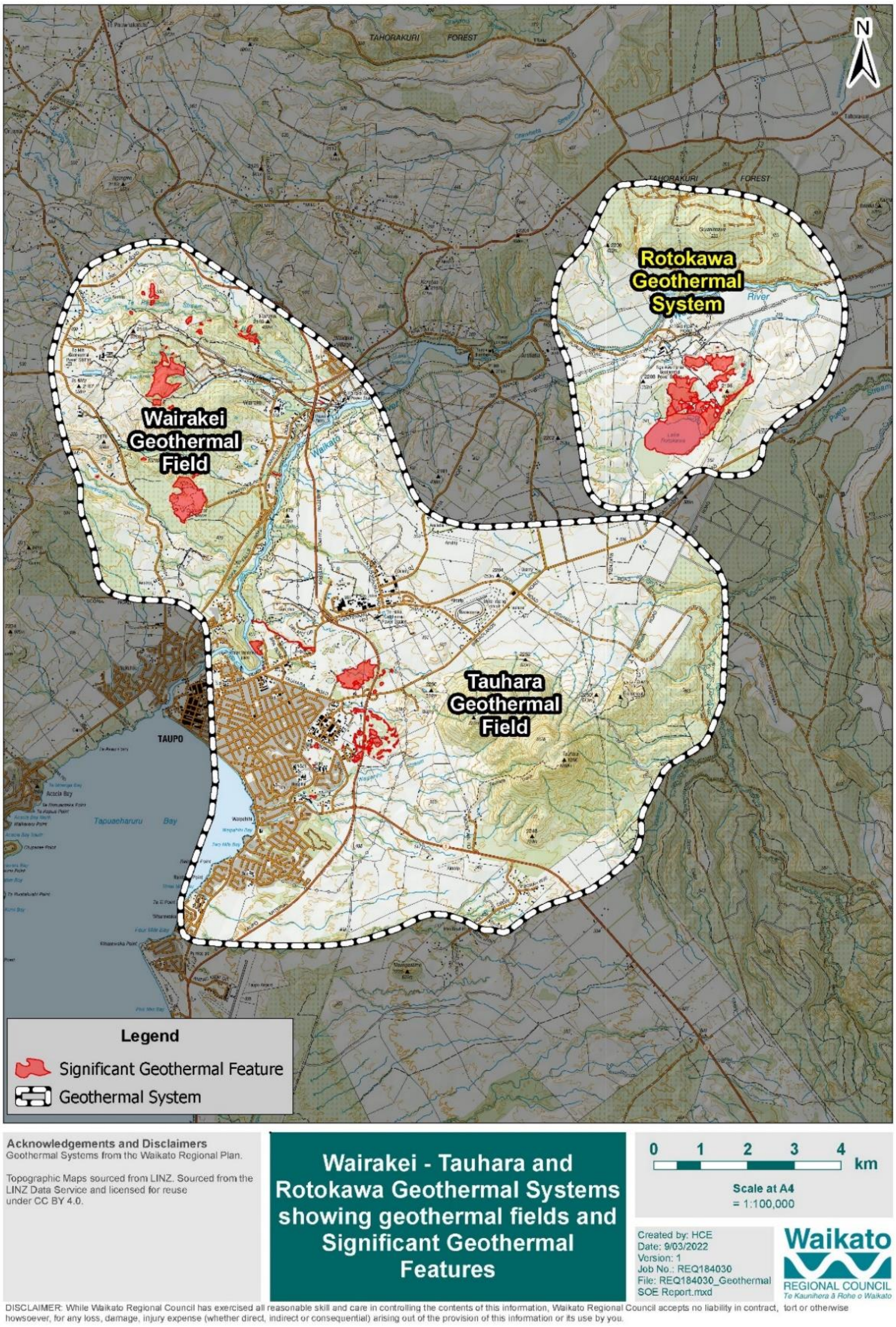


**Figure 3: Terminology: Geothermal Systems, Fields, and Significant Geothermal Features**

Some geothermal systems have many surface features while others have very few or none either because of natural reasons or because their surface features have been irreparably damaged by human intervention. Some geothermal features exhibit a wide range of natural variability in their discharge behaviour and extent of surface expression, while others remain quite stable over years and even decades. Some geothermal features are more highly valued for their natural characteristics, including their biodiversity and intrinsic values, than others. Some are more resilient to human intervention, resource development and land use than others. Some have been severely degraded by human activities, some have been moderately affected, and some are pristine. Although all geothermal features are rare in terms of the area of land they occupy internationally, nationally, and regionally, some are rarer than others.

## 2.2 Characteristics of the regional geothermal resource

Each system, field, and feature has a range of **characteristics**, including energy, mineralised fluids, biodiversity, topography, scenic and recreational values, and cultural values.

The Waikato Region's **regional geothermal resource** includes all geothermal water and energy, material containing energy or fluid (derived from within the earth) surrounding any geothermal water, all surface manifestations of geothermal processes, and all plants, animals, micro-organisms and characteristics dependent on geothermal water or energy, located in the region. This resource occurs throughout the Waikato Region, although its surface expression is most concentrated in the Taupō and Rotorua Districts (see Figure 2, which shows the locations of the regional geothermal resource within the Taupō Volcanic Zone).

The regional geothermal resource, the individual systems making up the regional resource, and the individual features within those systems each have their own set of geothermal characteristics.

Characteristics of the regional geothermal resource include:

i) Thermal energy contained in rocks and magma deep in the earth and carried by water
ii) Mineralised fluids (containing e.g. silica, lithium, and boron)
iii) The characteristics of all geothermal systems and features within it including the geophysical and biological features and processes associated with the surface expression of geothermal energy and fluids.

Characteristics of a geothermal system may include:

1) A body of thermal energy contained in rocks deep in the earth and carried by water
2) A convective inflow of cool, fresh water and a consequent outflow of heated mineralised fluids (containing e.g. silica, lithium, and boron)
3) Surface discharges of geothermal heat and mineralised fluids, such as springs and steam features
4) Land formations created by geothermal processes, such as hydrothermal eruption craters and sinter terraces
5) Biodiversity (a variety and uniqueness in genes, species and populations of plants, animals and micro-organisms).

Characteristics of a geothermal feature may include:

a) A surface discharge of steam, water, gases, and minerals
b) A flowing or standing body of water whose origin is either entirely or partly geothermal
c) Time-dependant behaviours such as intermittency of geysers
d) Infrequent or single eruptions such as hydrothermal eruptions and mud eruptions
e) Mineral depositions such as sinters and sulphur crystals
f) Mud volcanoes, mud flows, concentric mud ring patterns
g) Remnant geomorphological features such as hydrothermal eruption craters, geothermal collapse pits and associated caves
h) Heated or chemically altered ground
i) Terrestrial and aquatic geothermal ecosystems influenced by heat, humidity, and water and gas chemistry and flow.

The regional geothermal resource also has intrinsic, amenity, economic, social and cultural values. The extent and variety of natural characteristics of the regional geothermal resource provide a wide range of benefits. At times, geothermal characteristics highly valued by some people are developed at the expense of characteristics that may be highly valued by others. This has led to conflicts and a reduction in the extent and variety restricting the range of benefits available in future.

# 3 Geothermal resources of New Zealand

All but one of New Zealand's high-temperature systems are found in the Taupō Volcanic Zone, a zone of active volcanism that stretches from Mount Ruapehu in the central North Island to White Island in the Bay of Plenty and beyond (See **Error! Reference source not found.**). The W aikato Region has 16 known high-temperature systems and the Bay of Plenty region, 5 including Waimangu-Waikite-Waiotapu, which overlaps the boundary between the two regions. The Tongariro Geothermal System extends into Manawatu-Wanganui region. The only other high-temperature system is Ngawha, in Northland.

There are approximately 105 low temperature geothermal systems in New Zealand, with nearly a third of them being in the Waikato Region (See Mongillo and Cleland, 1984).

**Table 1: High-temperature geothermal systems of New Zealand (north to south)**

| Northland | Manawatu-Wanganui | Waikato | Bay of Plenty |
|---|---|---|---|
| Ngawha | | | |
| | | | White Island (Whakaari) |
| | | | Whale Island (Moutohorā) |
| | | | Kawerau |
| | | | Rotoiti-Tikitere-Taheke |
| | | | Rotomā-Tikorangi |
| | | | Rotokawa-Mokoia |
| | | | Rotorua |
| | | Waikite-Waiotapu-Waimangu | Waikite-Waiotapu-Waimangu |
| | | Horohoro | |
| | | Mangakino | |
| | | Atiamuri | |
| | | Te Kopia | |
| | | Reporoa | |
| | | Mokai | |
| | | Orakei Korako | |
| | | Ngatamariki | |
| | | Ohaaki | |
| | | Rotokawa | |
| | | Wairakei-Tauhara | |
| | | Horomatangi | |
| | | Tokaanu-Waihi-Hipaua | |
| | Tongariro | Tongariro | |
| | Ruapehu | Ruapehu | |

**Table 2: Low temperature geothermal systems (approximate numbers) (from Mongillo and Clelland 1984, Waikato numbers updated)**

| Region | No. of systems |
|---|---|
| Northland | 5 |
| Auckland | 5 |
| Waikato | 31 |
| Bay of Plenty | 20 |
| Gisborne | 1 |
| Taranaki | 3 |
| Hawkes Bay | 6 |
| Manawatu-Wanganui | 1 |
| Wellington | 0 |
| Nelson | 0 |
| Tasman | 0 |
| Marlborough | 0 |
| West Coast | 21 |
| Canterbury | 9 |
| Southland | 4 |

| Region | No. of systems |
|---|---|
| Otago | 0 |
| Chatham Islands Territory | 0 |
| **Total** | **105** |

# 4 Geothermal resources of the Waikato Region

## 4.1 Geothermal systems of the Waikato Region

The Waikato Region contains approximately 70 per cent of New Zealand's geothermal resources, in terms of the number of known high-temperature systems, and in terms of stored heat calculations (Lawless and Lovelock, 2001). There is a clear distinction between the region's large geothermal systems and its small geothermal systems. The large systems are all found in the Taupō Volcanic Zone. The small geothermal systems are scattered throughout the region, including the Taupō Volcanic Zone.

The region contains four active volcanoes (Ruapehu, Ngauruhoe, Tongariro and Lake Taupō (Horomatangi)), with all but Ngauruhoe hosting a large high-temperature geothermal system. The nature of the Horomatangi system is not well-known due to its deep lake-bed location. The Ruapehu system, including the crater lake (which sits just outside the regional boundary in the Manawatu-Wanganui region) comprises mainly surface water heated by volcanic gases rising into the lake and is only a few kilometres in extent, but has high temperatures (Ingham *et al.*, 2009).

There are sixteen known magmatic geothermal systems in the Waikato Region. Such systems contain large volumes of highly mineralised water and steam and extend over many square kilometres. They contain vast amounts of energy and most have surface features that are significant because of their rarity, vulnerability, and cultural, scientific and other values.

There are approximately 105 low-temperature systems in New Zealand, with approximately thirty of them found within the Waikato Region (Mongillo and Clelland, 1984). Most of the low-temperature systems are found outside the Taupō Volcanic Zone. These systems are discussed below as a group.

Some of the low-temperature geothermal systems in the Hauraki basin and the Coromandel coast are remnant volcanic systems, several of them accessing the same large body of cooling geothermal water (Hochstein, 1979).

Each of the 16 known large geothermal systems within the region is substantially different from the others in terms of its volumetric extent and land surface boundaries, local geology, reservoir dynamics, and surface outflows.

**Waikite-Waiotapu-Waimangu** system has many geysers, sinter-depositing springs, mud pools and other features, including the spectacular Champagne Pool at Waiotapu. There is a large tourist operation on the Waiotapu field, and one of the world's largest bee-keeping operations uses geothermal heat for warming hives and processing honey. Most of the Waimangu field is in the Bay of Plenty region. Waimangu is the youngest geothermal field in the world, having been created in the 1886 eruption of Mt Tarawera. It also has a large tourism operation. The process by which geothermal features and their associated ecosystems have evolved and continue to evolve here is of great interest to scientists. Waikite-Waiotapu-Waimangu is classified in the Waikato Regional Policy Statement as a Protected Geothermal System, meaning large-scale extractive use is prohibited to ensure the protection of geysers and sinter springs, and their dependent ecosystems.

**Horohoro** is a waning system, with few existing surface outflows but large areas of ancient sinter and several hydrothermal eruption craters, indicating that it has been substantially more active than it is today. A geothermally heated greenhouse grows flowers commercially. Horohoro is classified in the Waikato Regional Plan as a Development Geothermal System, meaning large-scale extractive uses may occur as long as significant adverse effects are avoided, remedied or mitigated.

**Mangakino** is the western-most large system in the Taupō Volcanic Zone. It also has few surface features, most of which now lie in the bed of the hydroelectric Lake Maraetai. However, it does not appear to be waning in the same way as Horohoro. Several attempts to drill into the hot resource have failed to intersect the expected reservoir. Mangakino is classified in the Waikato Regional Plan as a Development Geothermal System.

**Atiamuri** has two large sinter pools in a Department of Conservation reserve. There are several other sinter-depositing springs in nearby farmland, and some that were submerged by the creation of Lake Ohakuri. It is clear from the existence of extensive thick sinter deposits and sinter-lined craters that Atiamuri had a greater volume of geothermal fluid surface discharge than presently. Atiamuri is classified in the Waikato Regional Plan as a Limited Development Geothermal System, meaning that extractive uses may occur as long as there is no significant adverse effect on the vulnerable surface features.

**Horomatangi** lies under Lake Taupō, which is the caldera of an active volcano. Investigation with a submarine has revealed sinter spires and fumaroles on the bed of the lake (de Ronde *et al.*, 2002). Horomatangi is classified in the Waikato Regional Policy Statement as a Protected Geothermal System

**Te Kopia** is contiguous with the Orakei Korako system, and the two may be hydrologically linked. It has a relatively pristine area of geothermal vegetation extending from the base of the Paeroa Scarp to its top, all within a Department of Conservation Reserve and surrounded by mature forest, in a continuous sequence spanning 600 metres vertically. It has a rare mud geyser and many other pools at the base of the scarp, and several super-heated fumaroles pumping out large volumes of steam at the top of the scarp. Te Kopia is classified in the Waikato Regional Policy Statement as a Protected Geothermal System

**Reporoa** is contiguous with the Waikite-Waiotapu-Waimangu system, and may be hydrologically linked to it. Many of the sinter-depositing springs at Reporoa are adversely affected by drainage of the surrounding land for farming purposes. Reporoa is classified in the Waikato Regional Plan as a Research Geothermal System, meaning that not enough is known about the system yet to classify it into one of the other categories.

**Mokai** has its main upflow near the Mokai settlement, with a subsurface outflow flowing eleven kilometres north to the Waikato River. It has steam-fed surface features and few natural and physical resources that would be substantially adversely affected by subsidence, should it occur as a result of system development. Mokai system supports a geothermal power station, a 12-hectare green-house complex, a milk drying plant, and a trial hydrogen fuel production plant, all using geothermal energy. These industries, along with an offshoot composting facility that raises native plants for local riparian plantings, provide employment for many local people.

**Orakei Korako** has New Zealand's largest concentration of geysers and sinter-depositing springs, and supports a tourism operation. There are now approximately 35 geysers within the tourist area, but before the creation of hydroelectric Lake Ohakuri drowned a large part of the geyser field, there were approximately 120 geysers. Orakei Korako is a Protected Geothermal System.

**Ngatamariki** has unusual travertine sinters, but none of the springs vigorously deposit sinter. A geothermal power station operates on the system, which is a Development Geothermal System.

**Ohaaki** is a Development Geothermal System. It was developed in the 1970s for large-scale geothermal electricity production, but cold water drawdown near production wells has cooled the production aquifer and electricity output is decreasing. Before production commenced there were several geysers and sinter-depositing springs, including the spectacular Ohaaki Ngāwha, which is considered a taonga by Ngāti Tahu. The flow to these springs was destroyed by development, and now the Ngawha is kept full by a concrete plug and the input of bore water. Production has also increased the surface expression of steam, and an urupā has become the site of new fumaroles. The site of the main Ngāti Tahu marae, situated by the Waikato River, has experienced land subsidence as a result of development. It and surrounding land are now protected from inundation by the Waikato River by a bund. Subsidence has caused an important wetland to become deep water, and farmland has become wetland. As well as a geothermal power station, there is a geothermally-heated timber-drying plant and a trial plant for recovering minerals from the used geothermal discharged by the power station.

**Rotokawa** supports two power stations. An extensive area of altered ground has been the site of a sulphur-mining operation that ceased operations in the 1980s, and substantial sulphur deposits remain. The geothermal vegetation ecosystem continues to recover from the mining operations. Rotokawa has a few sinter-depositing springs, and a large area of geothermal vegetation. Lake Rotokawa is the largest geothermal lake in New Zealand, and has been shown to contain what is believed to be a unique species of leech, which is adapted to live in the highly acidic water with a pH of 2. Rotokawa is a Development Geothermal System.

**Wairakei-Tauhara** once supported two large geyser fields, at Wairakei Geyser Valley and Spa Sights in Taupō, but the flow to these was destroyed by the geothermal development for the Wairakei Power Station and may also have been affected by works in the bed of the Waikato River associated with the installation of the Taupō Control Gates for hydroelectric developments. In the 1990s the Waiora Lakes, an extensive area of geothermal lakes and pools of different colours in the north-west of the system dried up as a result of hydrological changes induced by development. The Wairakei Power Station has been operating since 1959. It was the second geothermal power station ever built in the world, and the first to tap wet steam. Part of the Wairakei field has experienced subsidence of up to 15 metres as a result of the geothermal development. Some of the Taupō urban area is built over part of the Tauhara geothermal field and has experienced a lesser degree subsidence believed to be caused by extraction from Wairakei. There are three geothermal power stations operating at Wairakei and one at Tauhara. Resource consents have been issued for another on the Tauhara field and drilling was underway in 2022. Timber processing, a prawn farm, and a tourist attraction of artificial sinter terraces all use geothermal fluid and energy. Craters of the Moon and the Wairakei Thermal Valley are tourist attractions on areas of geothermal activity whose discharge has been modified from water discharge to steam as a result of large-scale extraction. There are many geothermally-heated homes, motels, and swimming pool complexes. Wairakei-Tauhara is a Development Geothermal System.

**Tokaanu-Waihi-Hipaua** has several geysers and sinter-depositing springs at Tokaanu, most of which are in a Department of Conservation reserve. Waihi village also has hot springs at the edge of Lake Taupō, and directly above Waihi there is a large expanse of steaming ground on a steep hillside at Hipaua. This has been the site of several fatal landslides, as chemicals in the geothermal steam destroy the structure of the soil, causing it to slip away and fall onto the village. There are many small uses of geothermal fluid at Tokaanu, including homes, public baths, and accommodation establishments. Tokaanu-Waihi-Hipaua is a Limited Development Geothermal System.

**Tongariro** and **Ruapehu** in Tongariro National Park are New Zealand’s only two high-altitude large geothermal systems. Tongariro has outflows at Ketetahi, Te Maari, and the Tongariro summit. Ketetahi Springs is a taonga of Tūwharetoa and is on private property surrounded by the Tongariro National Park. Within Ketetahi Springs there are unusual acid geysers, and the geothermal area supports a high-altitude thermophilic midge that is not known to live anywhere else. Ruapehu has a volcanic crater lake overlying the geothermal system. Both Tongariro and Ruapehu geothermal systems extend into the Manawatu-Wanganui region. That part of Tongariro that is in the Waikato Region is a Protected Geothermal System. Ruapehu has not been classified in the Waikato Regional Policy Statement as yet because the geothermal system underlying the crater lake was discovered following the last revision of the Waikato Regional Policy Statement.

## 4.2 Geothermal features of the Waikato Region

The Waikato Regional Policy Statement (Waikato Regional Council, 2016) and Waikato Regional Plan (Waikato Regional Council, 2012) define some geothermal features as **Significant Geothermal Features**, based on an analysis of their rarity, vulnerability to changes induced by large-scale geothermal development or caused by other uses of land and water, and to natural influences such as weathering (Keam, Luketina and Pipe, 2005). The definition of significant geothermal feature types is reproduced below in Table:

**Table 3: Significant Geothermal Feature types**

| Feature type | Definition |
|---|---|
| Geyser | Any naturally occurring geothermal spring that occasionally or frequently erupts producing an intermittent or continuous discharge by the evolution of a phase dominated by steam or other gases, vigorous enough to eject forcefully liquid water by surging, boiling, throwing, splashing, or jetting it into the air above a static water level or vent opening. This includes hot water geysers, perpetual spouters, soda geysers, and crypto-geysers[1]. The area of a geyser comprises that of the spring basin and the area covered (perhaps intermittently) by surface water composed of the undiluted discharge from the geyser, and by any sinter deposits created by that discharge. |
| Spring vigorously depositing sinter | Any naturally occurring geothermal spring that vigorously deposits sinter on surfaces covered by its outflow, or any submerged geothermal spring that would be likely to vigorously deposit sinter if it were no longer submerged. The area of a spring vigorously depositing sinter comprises that of the spring basin, together with the area covered by any surface water composed of the undiluted outflow from the pool and any sinter deposits created by that outflow. |
| Recent sinter | Any sinter body that has received natural sinter deposition since 1900 but which is no longer receiving natural sinter deposition. This includes carbonate sinters (travertine). The area of a recent sinter body consists of that of all interconnected sinter in a single occurrence and the land formations underlying it. |
| Geothermal habitat on heated ground or cooled acid ground | Any area of terrestrial habitat of thermotolerant indigenous species on current or formerly geothermally heated ground. |
| Habitat dependent on geothermally-altered atmosphere | Any area of terrestrial habitat of indigenous thermotolerant species that is tolerant of, or dependent on geothermal alteration of, atmospheric conditions. |
| Mud geyser | Any naturally occurring geothermally heated mud pool that occasionally or frequently erupts. The eruption produces an intermittent or continuous discharge caused by the evolution of a phase dominated by steam or other gases. This must be vigorous enough to forcefully raise liquid mud by surging, boiling, throwing, splashing, or jetting it into the air above a static water level. This includes mud volcanoes exhibiting this behaviour. The area covered by a mud geyser includes |

[1] Crypto-geysers (meaning hidden geysers) are discharging geothermal features that exhibit the characteristic intermittency of a geyser except that they do not project columns or jets of water into the air. Generally, the intermittency is exhibited by regularly fluctuating water levels and discharge rates. Inferno Crater at Waimangu is the largest crypto-geyser that we know of, although when we monitor flows on a daily basis on smaller pools, we find there are others, such as the northern Whangapoa Spring.

| Feature type | Definition |
|---|---|
| | the mud pool, its banks, and any mud formations built up by the ejection of mud from the pool. |
| Molten sulphur-producing spring | A hot spring whose water supply passes through elemental sulphur bearing rock at a temperature sufficiently high to melt the sulphur (119°C) and bring it to the surface. |
| Superheated fumarole | Any naturally occurring vent, including those found underwater, whose main discharge consists of steam and other gases of geothermal origin with a temperature greater than the local boiling temperature of water. The area of a fumarole consists of the vent, any surface accumulating mineral deposits derived from its gases, and any ecosystems dependent on the heat and fluid flowing from the vent. |
| Mud pool | Any naturally occurring basin of turbid water or mud heated (or recently heated) by geothermal processes. The area of a mud pool comprises that of the pool itself, its banks, and any mud formations built up by the ejection of mud from the pool. |
| Geothermally-influenced aquatic habitat | Any area of naturally occurring seasonal or permanent aquatic habitat of thermotolerant, thermophilic, or extremophilic indigenous species in a water body or part thereof influenced by natural geothermal input, or in a geothermally-influenced water body. |
| Geothermally-influenced water body | Any naturally occurring wetland, lake, pool, or stream, or portion thereof (including the bed and banks), whose chemical or temperature profile is significantly influenced by natural geothermal input and which is either:<br>• a standing water body of greater than $30m^2$ surface area, or<br>• a flowing water body longer than 100 metres and with a flow greater than $0.1m^3$/sec<br><br>in which natural geothermal input has caused the water to have:<br><br>• a temperature of greater than 30°C, or<br>• a chloride concentration of greater than $120g/m^3$, or<br>• a sulphate concentration of greater than $60g/m^3$, or<br>• geothermal mineral deposition,<br><br>measured at least 7 days after a significant rainfall event.<br>In large or poorly mixed water bodies, only those portions which meet the above conditions are included in this definition. |
| Hydrothermal eruption crater | Any naturally occurring crater produced by the explosive boiling of geothermal water without the direct involvement of near-surface magma, and by the consequent ejection of material derived from the rock matrix. The area of a hydrothermal eruption crater comprises that of the crater, its sides, and the ejecta deposited around the crater. |
| Culturally significant feature | Any geothermal surface feature, whether artificial, natural, or modified that is deemed significant following consideration of the criteria for determining significance of cultural heritage resources in appendix 4 of the Waikato Regional Policy Statement. |

In addition to the feature types included in the table above because of their relative rarity and vulnerability, a special feature type, "Culturally significant features" is included. This allows for the protection of specific artificial or otherwise non-significant geothermal features that have attained outstanding cultural or scientific importance, according to the criteria for determining significance of cultural heritage resources, as set out in the Regional Policy Statement appendix 4. An example of a culturally significant feature could be Mokena Geyser at Te Aroha, which is in fact a geysering bore, but which has scientific, tourist and historical significance.

There are other geothermal features in the region that have not been included as significant. These include but are not limited to:

- fumaroles producing steam of less than 100 °C
- heated or steaming ground
- geothermally altered ground
- collapse pits
- geothermal springs or seeps, and
- ancient sinter.

# 5 Uses of the regional geothermal resource

Uses of the regional geothermal resource include:

a) an important thermal energy source for electricity generation at Wairakei-Tauhara, Ohaaki, Rotokawa, Ngatamariki and Mokai
b) domestic and commercial space heating by hot water and steam in the Taupō and Tokaanu urban areas
c) domestic and commercially operated thermal bathing pools and spas (e.g. Taupō, Miranda, Te Aroha, Tokaanu, Waingaro, Whitianga and Okauia)
d) commercial hot water operations such as prawn farming at Wairakei, tourism at Wairakei Terraces, commercial glasshouses at Horohoro and Mokai, and timber drying at Ohaaki
e) commercial extraction of minerals from geothermal water at Ohaaki
f) the scientific study of geothermal features, processes, and ecosystems
g) Māori traditional and contemporary use throughout the region
h) tourist, recreational and scenic attractions
i) a source of micro-organisms for industrial processes.

All of these uses have the potential to increase in scale and to expand into new areas. In addition, there is the potential for extraction of useful minerals such as silica, lithium, boron, gold, silver, and zeolites. Sulphur has been extracted at Rotokawa in the past and may be extracted somewhere in the region in the future.

Geothermal activity has high economic worth, as a source of low-carbon energy and as an important tourist attraction. The regional geothermal resource makes an important economic contribution locally, regionally and nationally. However, since the Covid-19 pandemic curtailed international travel in late 2019, the contribution of geothermal tourism has been significantly reduced.

In 2016, there were 905,000 visits by domestic tourists to geothermal sites in the Waikato Region, up from 450,000 in 2011. Geothermal attractions accounted for more than 16% of domestic tourism in the Waikato Region, up from 13% in 2012. In 2016 the Waikato Region had a total of 472,000 international visits to geothermal attractions (up from 290,000 in 2011) (Luketina, Olubode & Phillips 2017).

Assuming that on average, every visit to a geothermal attraction leads to spending of $50 (including entry fee (when charged), other spending at the site (e.g., food, souvenirs), and a component of overall trip expenses including travel and accommodation, geothermal tourism can be estimated to be worth approximately $110 million to the Waikato Region’s economy.

A 2001 survey determined that bathing was the most popular geothermal tourist activity, followed by visiting natural tourist attractions and technology-related tourist attractions such as the Prawn Park and the Wairakei Borefield Lookout.

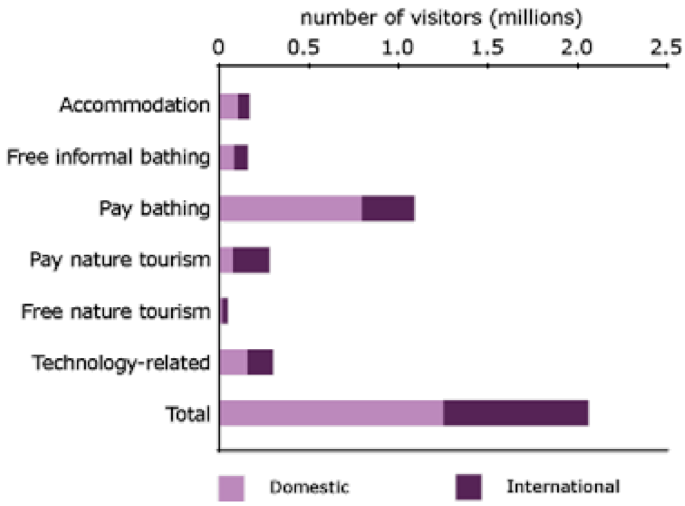

**Figure 4: Visitor numbers to geothermal attractions in 2001 (Luketina 2002)**

Visitor attractions can be managed in accordance with sustainable management principles, protecting and enhancing the geothermal resource and increasing awareness and understanding through education and interpretation. Surface outflows and muds have long been used for health treatments and promoting wellness.

Nationally, geothermal electricity production accounted for 18% of all electricity produced in 2020, according to the latest data that is available. (Ministry of Business, Innovation and Employment, 2021).

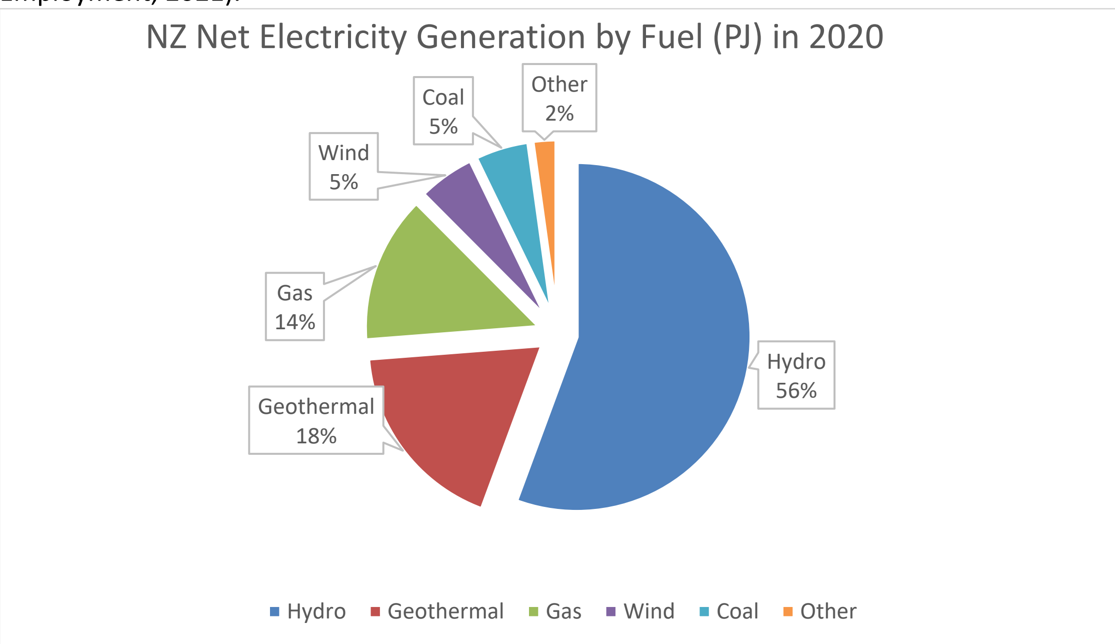

**Figure 5: NZ Net Electricity Generation (Ministry of Business, Innovation and Employment, 2021).**

The nine geothermal power stations in the Waikato region generated 6,230 GWh per year in 2019. This is 81% of the geothermal electricity generated in New Zealand, and 15% of the nation's electricity (Daysh et al, 2020).

Value added by geothermal electricity generation in 2016 was $106 million and associated employee count was 106. Geothermal tourism contributed less to Gross Regional Product than geothermal electricity generation ($74 million versus $106 million) but employed 10 times more people. (Luketina, Olubode & Phillips 2017).

Besides large uses, there are many other potential and existing smaller uses of geothermal energy and fluid that can be undertaken in these systems. However, some of the existing uses are productively inefficient because for technical reasons it is often easier to keep wells producing continuously, and they take and discharge more fluid than is needed for the purpose. In many cases, a single well can provide sufficient energy and fluid for the needs of several households. In cases where only heat, rather than heat and fluid, is required, the use of down-hole heat exchangers is a far more efficient use than taking and discharging fluid. While not having an effect on the deep aquifers, this can adversely affect the sustainability of the shallow aquifers that they take from, and associated geothermal features.

## 5.1 Growth of geothermal electricity generation in the Waikato Region

The Wairakei geothermal power station was the second large-scale geothermal power station in the world, and the first to harness the power of wet steam. The first power station, at Larderello in Italy, taps into a dry steam aquifer. Wairakei power station was commissioned over several years from 1958 to 1963. Ohaaki followed soon after, in 1989. Both these stations, developed under the era of 'Think Big' central government policies, the National Development Act and the oil shocks of the 1980s, had very little environmental consideration involved in their operations. Wairakei was discharging all its used geothermal fluid, with high concentrations of arsenic into the Waikato River. The pressure drawdown in the reservoir induced many changes in the natural flow of surface geothermal features including the extinction of many geysers and sinter-depositing springs. Subsidence west of the power station is more than 14 metres.

At Ohaaki the beautiful Ohaaki ngawha, a large steaming geothermal pool with an extensive sinter terrace dried up, as did geothermal springs beside the Waikato River including a geyser. The nearby urupā became heated ground, with steam rising through the graves. Compared to the large subsidence seen at Wairakei, which was mostly in a forested area with little infrastructure and therefore little subsidence-induced damage, a modest 2 m of extraction-induced subsidence led to the inundation of large areas of land next to the Waikato River.

It was not until the mid-2000s following the 10-year grace period allowed to existing operations that these two operations were re-consented under the Resource Management Act 1991 and the policies and rules of the Waikato Regional Policy Statement and Waikato Regional Plan.

The Poihipi Rd power station, which came online in 1996 and was then known as the McLachlan power station, was the first geothermal power station consented under the Resource Management Act 1991 and the Waikato Regional Council's policy instruments, and also the first following a legislation change sought by Mr McLachlan that allowed private ownership of electricity sources for public supply.

Since a relatively flat period in the 2000s when there was little increased demand for electricity, the last decade or so has seen a doubling in installed capacity as New Zealand's population grows and fossil fuel electricity sources are phased out (see Figure 6 and Table 4). A settled and enabling Waikato Regional geothermal policy, which provides developers with certainty about what can and cannot be done, and where, has also helped.

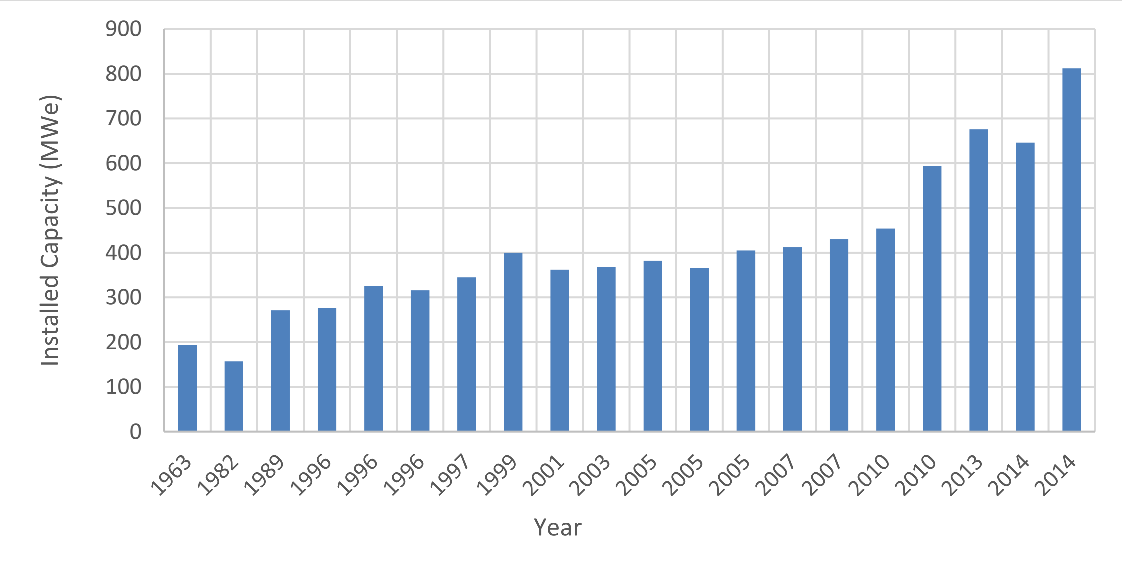


**Figure 6: Growth of geothermal electricity production in the Waikato Region (NZGA, 2022)**

**Table 4: Waikato installed capacity (NZGA, 2022)**

| Geothermal System | Project Name | Commissioning date | Installed Capacity (MWe) |
|---|---|---|---|
| Wairakei-Tauhara | Wairakei | 1963 | 193 |
| | Wairakei derating | 1982 | -36 |
| | Wairakei BP | 1996 | 5 |
| | Poihipi Rd | 1996 | 50 |
| | Wairakei Binary | 2005 | 14 |
| | Te Huka | 2010 | 24 |
| | Wairakei reduction | 2014 | -30 |
| | Te Mihi | 2014 | 166 |
| Current total installed capacity | | | 386 |
| Ohaaki | Ohaaki | 1989 | 114 |
| | Ohaaki rerating | 1996 | -10 |
| | Ohaaki derating | 2001 | -38 |
| | Ohaaki derating | 2005 | -16 |
| | Ohaaki rerating | 2007 | 7 |
| Current total installed capacity | | | 57 |
| Rotokawa | Rotokawa | 1997 | 29 |
| | Rotokawa extension | 2003 | 6 |
| | Nga Awa Purua | 2010 | 140 |
| Current total installed capacity | | | 175 |
| Mokai | Mokai | 1999 | 55 |
| | Mokai 2 | 2005 | 39 |
| | Mokai 3 | 2007 | 18 |
| Current total installed capacity | | | 112 |
| Ngatamariki | Ngatamariki | 2013 | 82 |
| **Current Waikato TOTAL installed capacity** | | | **812** |

## 5.2 Adverse effects on geothermal features

In some cases, large-scale extraction of energy and fluid has led to the demise of geysers, and to large scale increases in heat flow. Many significant geothermal ecosystems have been extensively modified or destroyed as a consequence although reinjection can reduce the damage and sometimes partially reverse it. There is no documented evidence to suggest all damage is reversible; instead, new flow regimes occur, and introduced species invade the modified habitats. Extraction can also increase the rate of steam discharge, enhancing steam-fed features such as hot ground and fumaroles. Where new surface outflows have occurred, existing land use has prevented or suppressed the establishment of geothermal ecosystems. As a result, natural geothermal ecosystems are extremely rare.

Already most of the region's geothermal features have been lost or degraded as a result of major electricity developments, either hydroelectric or geothermal. Most of the geysers at Orakei Korako are now underwater as a result of the creation of the hydroelectric Lake Ohakuri. Figure 7 shows the decrease in numbers of sinter-forming springs and geysers since the 1940s.

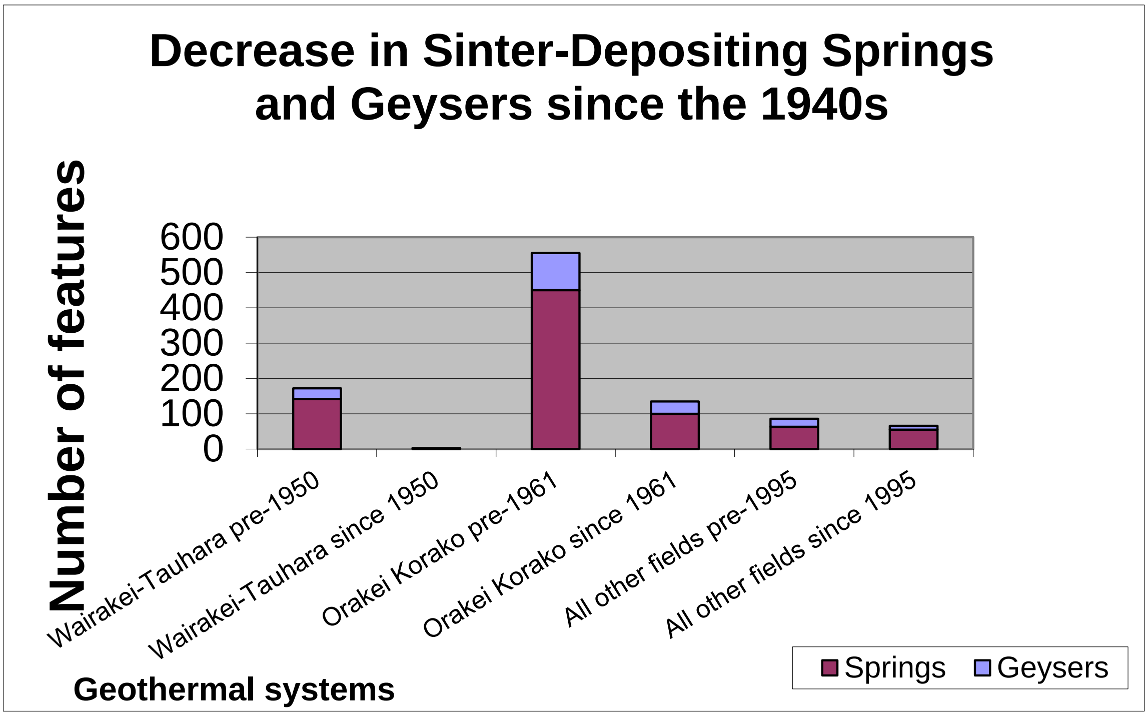


**Figure 7: Decrease in sinter-forming springs and geysers since 1950 (Cody et al., 2020)**

Many highly valued characteristics of geothermal systems and their surface features and dependent ecosystems are either under threat or already adversely affected from inappropriate use of the surrounding land. For example, at Reporoa, land drainage for farming has caused some sinter-depositing springs to cease discharging. Forestry in geothermal areas can lead to geothermal features being damaged by trees falling into them and harvesting machinery destroying delicate sinter terraces. Allowing livestock or vehicles access to geothermal features, or using geothermal features as rubbish dumps, can lead to a range of adverse effects including the crushing of fragile sinters and rare native plants, animals and micro-organisms. Spray drift and surface run-off can damage vegetation buffer zones and contaminate geothermal surface water, harming or destroying the native thermophilic ecosystems.

Land uses associated with the operation of a geothermal power station, such as roading and tracking, and the placement of bores, pylons, buildings, dumps, and other infrastructure, can destroy or adversely affect geothermal features if they are placed on or near them.

Geothermal tourism can lead to littering and vandalism. Building access roads, or paths for the tourists to walk on, can lead to contamination of pools and sinter by paving materials such as gravel or inundation from storm water. Native vegetation, including thermophilic species can be destroyed or contaminated with adventive exotic species. In some cases, features are drained or flows altered in order to preserve the paths that lead to or near them.

Subdivision and land development can restrict or prevent access to, and efficient use of, the geothermal resource.

## 5.3 Adverse effects on the environment from extractive uses

The life-supporting capacity of air, water, soils, and ecosystems can be degraded by artificial inputs of geothermal water, heat, and contaminants. Rivers and aquifers used for drinking water can have their water quality adversely affected, and river ecosystems can be degraded.

Although there is some natural discharge of geothermal energy and fluids into the Waikato River, artificial discharge, mainly from the Wairakei Power Station, has increased the concentrations of mercury, arsenic and boron in the water, and increased its temperature. This has long-term and short-term adverse effects on water quality and the riverine ecosystem. As a result of the combined effects of the natural and artificial geothermal discharges, and impoundment of water in the dams in the Waikato hydro-electric system, the beds of most of the Waikato River hydro-electric dams have high concentrations of arsenic in their sediments and have been officially classed as contaminated sites (Huser 2005). Some aquatic weeds and sediments harvested from the lakes for maintenance purposes must be disposed of in dedicated landfill sites due to their high arsenic concentrations.

At times, and in various locations, particular uses of geothermal resources have adverse effects on land uses. Large-scale extraction of geothermal fluid from geothermal systems has caused land subsidence, leading to loss of productive and culturally important land through flooding and change in contour, and damage to buildings and infrastructure. For example, large-scale geothermal fluid extraction at Wairakei-Tauhara and Ohaaki has led to land subsidence.

Extraction can also increase the rate of steam discharge through geothermal ground, increasing land instability and leading to hydrothermal eruptions, landslides, and the creation of tomos. In some cases, increased steam discharge, through the ground and infrastructure such as steam separators, pressure valves and cooling towers can cause steam hazards across roads and alter the microclimate in low-lying areas.

Shallow reinjection at various geothermal fields has led to increased discharge from springs, and ground inflation, both of which can cause property damage and adverse effects on existing land uses.

# 6 Sustainability, renewability & efficiency

Section 2 of the RMA (1991) defines energy produced from geothermal sources as renewable energy and section 7(j) requires particular regard to be had to the benefits to be derived from the use and development of renewable energy. These benefits include a reduction in the use of fossil fuels for electricity generation and hence a reduction in greenhouse gas and some other emissions (Denne, 20012) and its reliability independent of climatic conditions.

Renewability and sustainability are two different concepts. For an energy source, renewability describes a property of the resource, whereas sustainability relates to how the source is used [Stefansson, 2000; Thain, 2003]. For an energy source to be considered renewable, the rate of input of energy must be the same or greater than the rate of extraction over the period of renewability (see Figure 9). When discussing the renewability of any energy source, the timeframe for renewability needs to be specified. For example, coal deposits are renewable over geological ages, but not over a human timeframe.

In the case of electricity generation from a hydrothermal system, the rates of extraction of energy and fluid from the accessible reservoirs are generally far greater than the natural recharge rate. Recovery of the reservoir to the pre-extraction baseline is expected to take hundreds or thousands of years [Pritchett, 1998]. Therefore, the timeframe for renewability of geothermal resources is far greater than for other energy sources also considered renewable in section 2 RMA (1991) such as wind, wave, solar, hydro and biomass.

Studies show that the durations of typical hydrothermal systems range from 5,000 to 1,000,000 years [Thain, 2003]. During this time repeated pulses of heat may pass through the system for a time, and the area may retain some heat continuously for longer periods. These conditions may lead to temperature fluctuations and hydrodynamic variations during the history of the system. During a period of 1,000,000 years, erosion, deposition, and tectonic processes may also affect the hydrology of a geothermal system. On a geological timescale high-temperature individual geothermal systems are essentially ephemeral.

Most energy sources generally classed as renewable are either essentially unaffected by use (solar, wind, wave, tidal) or take no more than a few years to recover their energy-producing capacity (hydro, biomass). However, extraction of the fluid and energy in a geothermal system beyond the natural rate of discharge depletes the usable resource found within the upper aquifers. Recovery of a severely depleted aquifer by the replenishment of fluid and energy from lower depths to a point where it is economic to resume some production is expected to take a similar duration to that of the initial production [Pritchett, 1998; Ledingham, 1998; Rybach *et al.*, 2000].

Any large-scale extraction of geothermal fluid and energy at a rate equal to or greater than the rate of renewal will inevitably affect any dependent ecosystems. It also can destroy geothermal surface features. However, if the extraction of energy from a geothermal system, is less than this, then only extremely small developments could proceed. Much of the resource would therefore not be available for extractive use by current, and the next few, generations. Such a restrictive management regime would not promote sustainable management of the regional geothermal resource.

Total reinstatement of the heat and mass flux regime within a depleted geothermal system is theoretically possible only after an infinite time, but recovery to about 98 per cent of pre-production rates will take hundreds of years (Luketina, 2005). Figure 8 shows the projected response of the springs at Geyser Valley, Wairakei from continued large-scale take from the field until 2050 followed by cessation of take (from O'Sullivan and Mannington (2005))

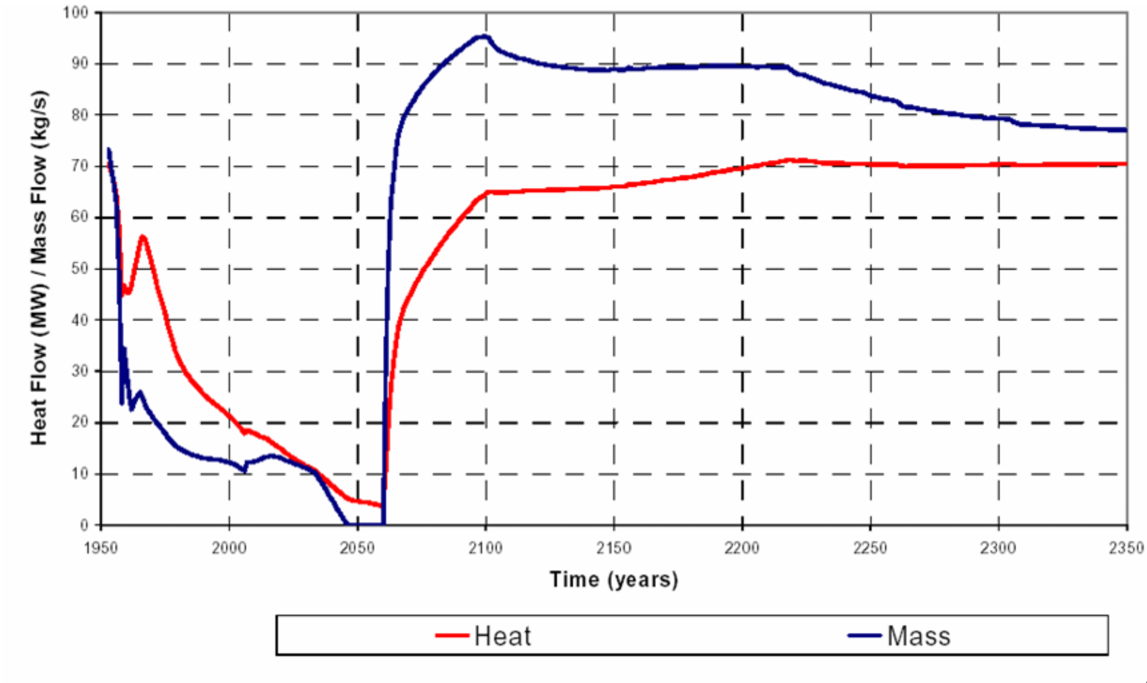


**Figure 8: Heat and mass flows at Geyser Valley (from O'Sullivan and Mannington, 2005)**

Sustainability can refer to either weak or strong sustainability. Strong sustainability requires no loss of natural resources, and thereby provides future generations with at least the opportunities of today's generation. However, weak sustainability allows the depletion of some natural resource stocks, as long as future generations will still be at least as well off as today's generation, through technological change, identification of previously unknown resource and the like.

Geothermal resources can be used sustainably (using a definition of weak sustainability) over any given period through controlled depletion. As with renewability, the timeframe for sustainability must be specified (see Figure 9). To sustain the energy-producing potential of a geothermal system to meet the reasonably foreseeable needs of future generations, extraction must be at a rate that can be reasonably expected to be maintained by those future generations. The depletion of the available energy and fluid in a geothermal reservoir within one or two generations, leaving the reservoir in a state where recovery of natural outflows will take hundreds or thousands of years, falls short of sustainable management of the resource.

In addition, it is desirable that the use of the resource is efficient, otherwise more resources will be demanded than is necessary for a given purpose, and additional environmental costs may occur. Another issue with sustainability is need versus want, and the continued demand for a higher standard of living, with a concomitant demand on energy sources and other resources.

The rate of conversion of heat and kinetic energy from geothermal fluid to electricity ranges from about 8 per cent for older power plants to 21 per cent for more efficient modern plants. As a general rule, no more than approximately 10 per cent of the heat and kinetic energy in geothermal fluid is converted to electricity [Sinclair Knight Merz, 2002].

For various reasons it is impractical or uneconomic to extract the remaining energy for electricity production, although in some cases it is used for direct heat applications. The used geothermal fluid is then either reinjected into the geothermal system, where it can be entrained back into the convective cycle. This helps to maintain reservoir pressures at an optimal level that balances recharge and limits adverse effects such as subsidence and changes in surface features. If discharged elsewhere, generally to surface water, unconnected underground strata, or onto the ground, the energy, fluid and minerals are lost from the geothermal system and may contaminate natural and physical resources. Therefore, reinjection into the system, or into an area where the fluid will find its way back into the system, is usually more energy-efficient than other discharge methods as it not only retains the unused energy in the discharged fluid, but continues to act as a 'working fluid' that entrains heat from the rock matrix for further use in the recirculation process. It has the added benefit of maintaining reservoir pressure, thus limiting other adverse effects such as subsidence.

In addition to the energy equation aspect of sustainability, environmental sustainability is concerned with the maintenance of processes on which all life depends. The OECD [2001] has identified four specific criteria that need to be met to ensure environmental sustainability.

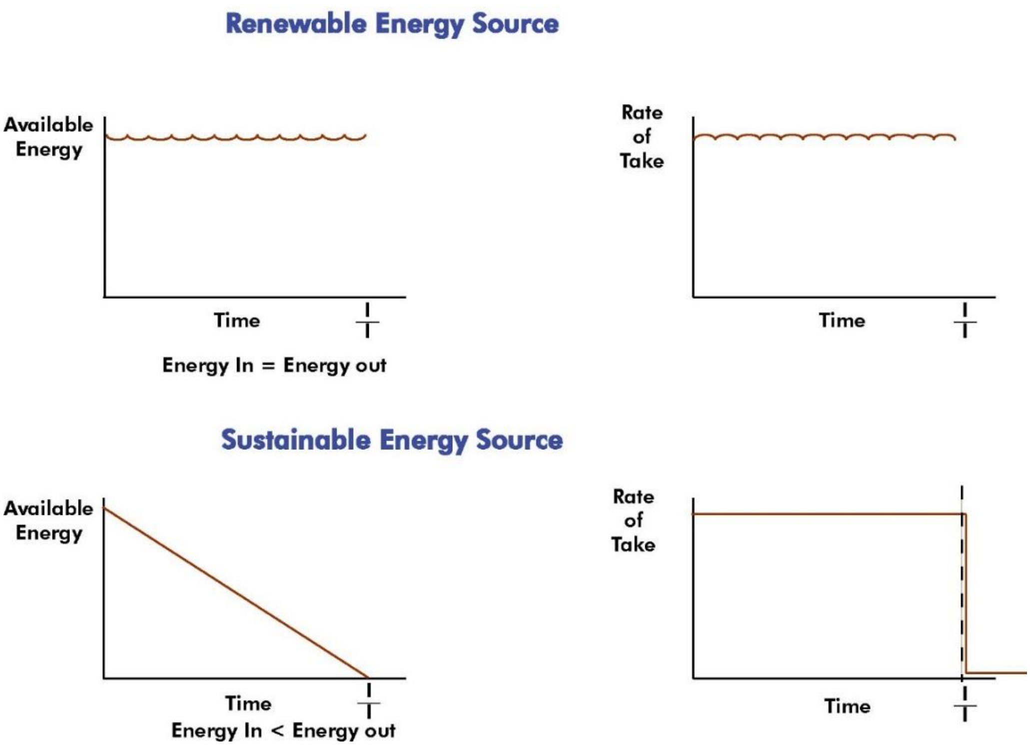

**Figure 9: Renewable and Sustainable Energy Sources**

These are:

1) regeneration: using renewable resources efficiently and not permitting their use to exceed their long-term rates of natural regeneration
2) substitutability: using-non-renewable resources efficiently and limiting their use to levels that can be offset by substitution of renewable resources or other forms of capital
3) assimilation: not allowing releases of hazardous or polluting substances to the environment to exceed the environment's assimilative capacity
4) avoiding irreversibility: avoiding irreversible impacts of human activities on ecosystems

However, the principles of sustainable management applied to the geothermal resources of the region take into account a great deal more than the ability to extract energy and water over a particular period, from a single system. From a regional perspective, sustainable management can be promoted by balancing resource demands across the region to provide for social, economic and cultural well-being whilst avoiding, remedying, or mitigating adverse effects. Some systems are allocated for efficient energy use and development whereas other systems will be protected from large-scale use and development. This is the approach of the Geothermal section of the Waikato Regional Policy Statement, which sets out a range of classifications for geothermal systems.

Efficient use of energy, as required by section 7 of the RMA (1991), includes several dimensions: productive efficiency (output at a low overall cost); allocative efficiency (allocating resources to production that society values the most); and dynamic or innovative efficiency (where technological change is encouraged and used to produce productivity gains). Conflicting and unclear objectives can lead to wasteful take and discharge resulting in greater loss of heat and fluid than would otherwise be required for the purpose. This is inconsistent with sustainable management and the principle of productive efficiency. Wasteful use can also occur, with geothermal resources being used in the place of more appropriate sources of heat, water, or minerals. This can deprive current and future generations of the ability to use the resource appropriately, and is inconsistent with the principle of allocative efficiency.

## 6.1 Reinjection and injection

The major portion of geothermal energy is heat within rocks and is primarily accessed through the extraction or circulation of geothermal fluid. The portion of extracted geothermal resource that is not taken from the fluid is discharged to the environment, typically by reinjection of the cooled fluid back into the geothermal system so that the remaining energy and fluid can be recirculated and used to maintain reservoir pressures. Minerals and chemicals included in the reinjected fluid may also be extracted for industrial and other uses.

Targeted reinjection to the system can also sustain reservoir pressures and minimise subsidence, the risk of hydrothermal eruptions, and adverse effects on geothermal surface features.

Once used in a primary process such as electricity generation, a geothermal resource may be of value to secondary, downstream industrial and/or domestic processes. Such a cascaded use of the resource contributes to the efficient use and development of that resource. In some cases, the high temperature clean steam is more valuable for industrial use than for electricity generation. However, where reinjection or injection is practised, the fluid may need to remain above a certain temperature or be acid-dosed to ensure a low pH to prevent deposition of minerals leading to clogging of pipes and the injection zones.

In some cases, particularly where the natural fluid of a geothermal system has been depleted by extraction without reinjection, injection of additional fluid to the system can assist use of the resource by providing a greater volume of extracted fluid from which to extract the energy resident in the system. This additional fluid can be water from any source including fresh water, wastewater, and sea water.

Some geothermal systems consist of hot dry rock with little or no convective cycle bringing hot fluid to the surface. The heat from these systems can be accessed by injecting water or gas and creating an artificial convection cycle by means of wells. While none of these systems have been developed in the Waikato Region, it is appropriate to allow for the possibility that they may be in the future.

When geothermal fluid is extracted from a geothermal reservoir, it transports energy and minerals during the extraction and replenishment processes. The fluid is replenished by natural upflows, reinjection, and sometimes by an artificial increase in fluid flow as a result of extraction. Provided appropriate management approaches are used to avoid significant land disruption, reservoir cooling and other adverse effects, reinjection can be beneficial by avoiding or mitigating land subsidence reducing the discharge to other natural and physical resources, and helping to sustain the natural flow to geothermal features.

The use of a geothermal system involves control of the interactive dynamic flows of energy, minerals and fluid through subterranean material with highly variable properties over areas of tens of square kilometres, to depths greater than five kilometres. This control requires input from many specialised technical disciplines, precise location of fluid takes and discharges, and long-term planning and investment.

## 6.2 Geothermal system resource assessment

In 2002 Waikato Regional Council commissioned an assessment of the electricity generation potential of its geothermal systems (Sinclair Knight Merz, 2002). This was done using a stored heat method, and was assessed for different periods ranging from 30 years to 300 years. Since then, the Waikato Regional Policy Statement has settled on a sustainable take period of several generations being sufficient to provide for the reasonably foreseeable needs of future generations. Depending on the size of a geothermal system, and how long it has been used already, this more or less equates to 100 years.

Waikato Regional Council policy encourages staged development of Development Geothermal Systems, whereby a relatively small power station is built as a first step that places a light load on the system dynamics. Monitoring the resulting perturbations in system response leads to greater understanding of what the limits of sustainable take are for the system and enable adaptive management of the resource.

Subsequently, the United Nations Framework Classification for Resources (UNFC) has developed for countries, companies, financial institutions, and other stakeholders a tool for sustainable development of energy and mineral resource endowments. UNFC applies to energy resources including oil and gas; renewable energy; nuclear energy; minerals; injection projects for the geological storage of $CO_2$; groundwater; and the anthropogenic resources such as secondary resources recycled from residues and wastes. The geothermal assessment was developed by the UN, the International Geothermal Association (IGA), and the International Renewable Energy Association (IRENA).

In 2017 the UN Economic Commission for Europe (UNECE, 2017) published an assessment of Ngatamariki under this framework as a case study. The assessment was undertaken in May 2015 using 2011 data. Using a power density method, the sustainability was determined to be 86 MWe per year for 30 years. Since then more has been learnt about the system dynamics as a result of monitoring its response to development. Furthermore, in 2016 an updated set of specifications was developed for geothermal resources.

Table 2 below shows the installed capacity versus the theoretical sustainable take over a period of 100 years for the five Waikato geothermal systems currently producing electricity.

Although Campen et al. (2019) called for a comprehensive assessment of Waikato geothermal systems, that project remains unfunded by Waikato Regional Council. It is reasonable for it to become a requirement of resource consent applications and annual resource consent reporting.

**Table 2: Installed capacity and theoretical sustainable take for Waikato Development Geothermal Systems**

| Geothermal System | Installed Capacity (MWe) | Sustainable take (MWe) (Sinclair Knight Merz 2002) | Sustainable take (MWe) (UNFCC) |
|---|---|---|---|
| Wairakei-Tauhara | 386 | 249 | Unknown |
| Ohaaki | 57 | 39 | 75 MWe for 30 years (Campen *et al.*, 2019) |
| Rotokawa | 175 | 90 | |
| Mokai | 112 | 42 | Unknown |
| Ngatamariki | 82 | 36 | 86 for 30 years (UNECE 2017) |
| Horohoro | 0 | 1 | Unknown |
| Mangakino | 0 | 14 | Unknown |

## 6.3 Information management

Sustainable management of a resource requires understanding of the characteristics of that resource. Management of the resource is improved by greater availability of relevant information.

The nature of the geothermal resource is such that there is a relative lack of knowledge. Surface features, where they exist, provide only a very small indication of the extent of the resource and its hydrodynamic characteristics. Geophysical and geochemical techniques, as well as an understanding of the local geology, must be applied to enable understanding of the resource. However, the level of knowledge varies from system to system.

Previously, much of this data and information has not been readily accessible to the public either because of the limitations of the information systems or because of the format in which the information has been presented. In addition, much data and information about the regional geothermal resource that was collected by the government using public funds is now retained in confidence by the government as a commercial asset, as is most new data collected. The unavailability of this data and information to regional and local authorities, to the public (including independent researchers) and to resource users creates uncertainty in decision-making, limiting the opportunities for use of the regional geothermal resource. It also can lead to higher costs for ratepayers and resource users through duplication.

Efficient use of the regional geothermal resource involves the efficient extraction (take) from the resource and the efficient application (use) of what is taken. Efficient take of geothermal fluid and energy in a development system is generally encouraged by:

a) integrated and co-operative development of the geothermal system
b) the absence of competitive extraction of fluid or energy from the system
c) consent conditions that reduce environmental risk and provide certainty
d) effective and efficient monitoring and evaluation of the resource state
e) a publicly agreed staged-development plan for each geothermal system spanning short, medium- and long-term time frames, and
f) public access to peer reviewed resource models, predictions, development scenarios and data.

Efficient use of the taken resource is encouraged by:

a) competition for the extracted resource (e.g. fluid and energy),
b) pricing the resource (to discourage waste) and
c) security of supply.

The geothermal resource is different from other resources because:

a) knowledge of the resource is usually very limited – especially at the early stages of development
b) geothermal systems are extremely complex, dynamic and interconnected
c) geothermal systems are unobservable and relatively inaccessible
d) geothermal cause and effect relationships are not usually well understood (but becoming better understood over time), and there is often a considerable time delay between cause and effect
e) the costs and risks of developing geothermal systems are very high.

Consequently "ideal" solutions are uncertain because of the lack of understanding of the functioning of a system. Early stages of development will have a strong element of trial and error, and require iterative approaches. As more information is collected, system operations can be better designed to optimise efficiency. This relies on, and assumes, good physical access to all of the land above the resource. Limitations to land will potentially affect the operator's ability to optimise efficient system development.

The inaccessibility of geothermal systems means that knowledge comes from surface features, surveys (especially geophysical) and from data at certain points within the system. Data is then modelled, cross checked, used to explore different development scenarios and only allows tentative conclusions. As the system is developed, knowledge increases, as more data is available for modelling. This lack of certainty is exacerbated by technical disagreements between experts. This has implications for identifying the effects of using the resource, but also for the developer to optimise production.

Adverse effects of take, use and discharge of the geothermal resource are difficult to assign to one of multiple operators because of uncertainty around cause and effect relationships. Remedying adverse effects relies on a co-ordinated and integrated approach and understanding. Again, land access will affect the effectiveness of response.

Good quality data and information is essential for robust policy development and good decision-making.

Under RMA s35, regional councils have a duty to gather information regarding the state of the environment, and to keep records of that information. For that reason, Waikato Regional Council undertakes monitoring and investigation into the extent, variety and condition of the regional geothermal resource and its characteristics, and into the effects of geothermal resource use on the resource and other natural and physical resources. This material has been collected under a wide range of conditions, for various purposes, and over time by developing technologies.

Much geothermal resource data and information has already been collected, and will be collected by resource consent holders. It is important that information derived from this data is peer reviewed to ensure that interpretations (including models and scenarios) reflect expert consensus rather than a high risk or extreme position. It is also important that different interpretations of the data are encouraged, to avoid assumptions becoming entrenched without question.

Collection, maintenance and dissemination of geothermal information are critical for effective resource management, both regionally and nationally. Transparent public access to geothermal resource data and information can promote public confidence in management and foster public appreciation of the resource.

# 7 Waikato Regional Council reports

The following section describes some examples of the monitoring output of the Waikato Regional Council geothermal monitoring programme.

## 7.1 Terrestrial Ecology

**Table 3: Geothermal terrestrial ecological studies**

| Study | What | Previous | Last | Next Due | Expected date |
|---|---|---|---|---|---|
| **Vegetation** | Regional extent and condition | 2000, 2003, 2004, 2012, 2014[2] | 2015[3] | 2022 | 2022 |

[2] Wildlands Consultants Ltd 2000, 2003, 2004, 2012, 2014
[3] Wildlands Consultants Ltd 2015

| Study | What | Previous | Last | Next Due | Expected date |
|---|---|---|---|---|---|
| **Vegetation** | Selected sites extent and condition | Numerous records from 1979 onwards referenced in the above documents and in 2021[4] | | | Unfunded |
| **Priority sites for biodiversity management** | | 2011a, 2011b[5] | 2015a, 2015b[6] | 2017, 2021 | Unfunded |
| **Ecological reporting** | | | 2016[7] | 2017, 2021 | Unfunded |
| **Ecosystem Services** | | | 2018[8] | | Unfunded |
| **Matauranga Maori values** | | Unfunded | Unfunded | Unfunded | Unfunded |
| **Soil invertebrate macrofauna** | Survey | 2012[9] | 2013[10] | | Unfunded |
| **Terrestrial insects And Ecological condition assessment tool** | Biodiversity | | 2015[11] | | Unfunded |
| **Lizards** | Survey | | 2022[12] | | |

## 7.2 Aquatic Ecology

**Table 4: Geothermal aquatic ecological studies**

| Study | What | Previous | Last | Next Due | Expected date |
|---|---|---|---|---|---|
| **Standing waters invertebrates** | | 2000[13] | | | Unfunded |
| **Flowing waters invertebrates** | | 2001[14] | | | Unfunded |
| **Flowing waters habitat characteristics** | | 2005[15] | | | Unfunded |
| **Lakes habitats** | | 2015[16] | | | Unfunded |
| **Microbial diversity** | 1000 Springs - GNS | 2015[17] | | | Unfunded |

[4] Wildlands Consultants Ltd 2021
[5] Wildlands Consultants Ltd 2011a, 2011b
[6] Wildlands Consultants Ltd 2015a, 2015b
[7] Wildlands Consultants Ltd 2016
[8] Wildland Consultants 2018
[9] Willoughby and Blakemore 2012
[10] Willoughby and Beard, 2013
[11] Willoughby and Beard, 2015
[12] Brodnax, 2022
[13] Duggan and Boothroyd, 2001
[14] Duggan and Boothroyd, 2002
[15] Stevens et al., 2003
[16] Catlin et al., 2015
[17] Power et al., 2017

**Table 5: Geothermal geochemistry surveys**

| Study | What | Previous | Last | Next Due | Expected date |
|---|---|---|---|---|---|
| **Geochemistry** | Spatial and temporal trends | 1996[18], 2007[19], 2008[20], 2010[21], 2013[22] | 2018[23] | 2022[24] | June 2022 |

**Table 6: Geothermal features physical characteristics**

| Study | What | Previous | Last | Next Due | Expected date |
|---|---|---|---|---|---|
| **Definition of Significant Geothermal Features** | | 2005[25] | | N/A | |
| **Geyser periodicity** | | 2002[26], 2013[27] | 2015[28] | | Unfunded |
| **Sinter Springs** | Number and condition | 2002[29] | 2020[30] | - | Unfunded |
| **Quarterly and annual monitoring[31]** | 60 selected features | Since 1990 | | 2022 | December 2022 |

**Table 7: Geothermal geophysical studies**

| Study | What | Previous | Last | Next Due | Expected date |
|---|---|---|---|---|---|
| Resource estimate | | | 2002[32] | | Unfunded |
| System boundaries | | | 2002[33] | | Unfunded |
| Thermal Infrared | Geothermal features imaged to determine location and heat output | Several small sites throughout the region | 2016[34] | | Unfunded |
| 3-D imagery | Geothermal terrain imaged to see relief and vegetation height | Waimangu | 2018[35] | | Unfunded |
| Hydrothermal Eruption Craters | Mapping of craters | Horohoro and Tauhara | 2007[36] | | Unfunded |
| Tauhara | Stratigraphy and use of shallow resource | | 1988[37] | 2022[38] | 2022 |

[18] Huser and Jenkinson, 1996
[19] Luketina, 2007
[20] Webster-Brown and Brown, 2008
[21] Webster-Brown and Brown, 2010
[22] Golder Associates Ltd, 2013
[23] Wilson, 2018
[24] Pope and Christenson, 2022
[25] Keam et al, 2005
[26] Cody, 2002b
[27] Nikrou et al., 2013a, 2013b
[28] Newson and McKibbin, 2015
[29] Luketina and Cody, 2002
[30] Cody et al., 2020
[31] See Cody AD 1996 – 2005, Lynne B 2007b, 2008, 2009, Newson J, 2010, 2011, and WRC reports from then on available on WRC website or by request.
[32] Sinclair Knight Merz 2002
[33] Risk GF 2000a, 2000b, 2003, Luketina 2005
[34] Harvey et al., 2016
[35] Harvey, 2018
[36] Lynne, 2007a
[37] Curtis, 1988
[38] Lebe, 2022

| Study | What | Previous | Last | Next Due | Expected date |
|---|---|---|---|---|---|
| Onekeneke | Stream characteristics | 1993[39], 1995[40] | 2015[41] | | Unfunded |
| Mangakino | System characteristics | | 2016[42] | | Unfunded |

**Table 8: New techniques**

| Study | What | Previous | Last | Next Due | Expected date |
|---|---|---|---|---|---|
| **Ground Penetrating radar** | Buried sinter | Armstrong reserve, Taupō | 2016[43] | | Unfunded |
| **Aerial photography/ vegetation condition** | TIR, NIR, Visual vs ground assay | Craters of the Moon | 2015[44], 2016[45] 2018[46] | | Unfunded |
| **$CO_2$ flux and Thermal Infra-red aerial photography** | System extent | 2018[47] | 2020[48] | | Unfunded |
| **PSInsar** | Ground deformation | Wairakei Ngatamariki and Tokaanu[49] Taupo Volcanic Zone[50] Tauhara[51] Rotokawa[52] Ohaaki, Mokai, Orakei Korako, Te Kopia, Ongaroto Reporoa Atiamuri Waiotapu - Waikite Waimangu, Horohoro Tongariro White Island-Whakaari | 2019[53], 2021[54] | | Unfunded |

**Table 9: Economic value of geothermal resources**

| Study | What | Previous | Last | Next Due | Expected date |
|---|---|---|---|---|---|
| **Economic value of geothermal uses** | | 2002[55], 2011[56], 2018[57] | | | Unfunded |

[39] Cody, 1993
[40] Cody, 1995
[41] Luketina et al., 2015
[42] Rustandi et al., 2016
[43] Lynne et al., 2016
[44] Harvey and Luketina, 2015
[45] Lloyd et al., 2016, Harvey, Harvey et al., 2016, Harvey, Rowland and Luketina, 2016
[46] Harvey, 2018
[47] Harvey et al., 2018
[48] Harvey, 2020
[49] Harvey, 2022a
[50] Harvey, 2022b
[51] Harvey 2022c
[52] Harvey 2022d
[53] Harvey et al., 2019
[54] Harvey et al., 2021
[55] Luketina, 2002
[56] Barns and Luketina, 2011.
[57] Luketina et al., 2018

**Table 10: Small Geothermal Systems resource assessment**

| Study | What | Previous | Last | Next Due | Expected date |
|---|---|---|---|---|---|
| **Kaimai** | Water chemistry | | 2017[58] | | |
| **Lake Waikare** | System characteristics | 2015[59] | 2016[60] | | Unfunded |
| **Miranda-Kaiaua** | System extent | | 2012[61] | | Unfunded |
| **Motuoapa** | System characteristics | | 2016[62] | | Unfunded |
| **Ohinewai** | Economic opportunity | | 2015[63] | | Unfunded |
| **Okauia** | System characteristics | | 2015[64] | | Unfunded |
| **Te Aroha** | System extent | | 2013[65], 2015[66], 2018[67] | 2022[68] | Nov 2022 |
| **Waitoa** | System characteristics | | 2015[69] | | Unfunded |

# 8 Understanding geothermal resource use and effects dynamics

## 8.1 Performance against ERAs

For geothermal resources, Section 15.4.6 of the Waikato Regional Policy Statement has thirteen Environmental Results Anticipated (ERAs) from the application of its policy instruments. These are reproduced below:

"15.4.6 Geothermal

a) Tāngata whenua have a greater role in the management of the Regional Geothermal Resource.
b) There is greater public awareness of the characteristics of geothermal resources, including Significant Geothermal Features.
c) Adverse effects on Significant Geothermal Features are managed consistently with the relevant Geothermal System Classification.
d) Some geothermal energy available for use by present and future generations.
e) Land use, development and use of non-geothermal water are compatible with the purpose for which geothermal systems are classified.
f) Adverse effects on Significant Geothermal Features from the development and uses of non-geothermal water and the new development and uses of land are avoided, with the exception of existing effects from the operation of the Waikato River system for hydroelectric generation.
g) Large-scale use of geothermal energy and water are enabled in Development Geothermal Systems.

[58] Ramadhan et al., 2017
[59] Balane et al., 2015a
[60] Balane et al., 2015b
[61] Peter et al., 2012
[62] Murgulov et al., 2016
[63] Cheptum et al., 2015
[64] King, 2015
[65] Murithi, 2013
[66] Moodie et al., 2015
[67] Turk and Luketina, 2018
[68] Moodie et al., 2022
[69] Mutonga et al., 2015

h) Adverse effects on other natural and physical resources, including overlying structures, from take, use and discharge of geothermal energy and water are avoided, remedied, or mitigated.
i) The risk of hydrothermal eruptions is reduced.
j) Economic benefits derived from access to some of the energy and other geothermal characteristics, including non-extractive uses, and to Significant Geothermal Features.
k) Understanding of the Regional Geothermal Resource and the characteristics of Research Systems through controlled research of these systems is increased.
l) In situ uses of geothermal energy are increased.
m) There is increased protection for the full range of geothermal features.
n) Research Geothermal Systems are reclassified as Development, Limited Development or Protected Geothermal Systems.
o) There is increased use of energy- and water-efficient technologies and more efficient use of the Regional Geothermal Resource."

In addition, Section 7.7 of the Waikato Regional Plan lists nine Environmental Results Anticipated from the application of its policy instruments. These are reproduced below:

"7.7 Environmental Results Anticipated

1. The sustainable management of the Regional Geothermal Resource
2. People and communities being able to provide for their social, economic, and cultural wellbeing through the appropriate use, development and protection of the Regional Geothermal Resource.
3. Geothermal surface features and resource management matters of significance to tangata whenua identified, and recognised and provided for.
4. Efficient use of the Regional Geothermal Resource including the use of alternative technologies such as down-hole heat exchangers.
5. Significant adverse effects on Significant Geothermal Features in Development Geothermal Systems arising from the take, use, and discharge of geothermal energy and water remedied or mitigated in any Geothermal System.
6. No significant adverse effects on Significant Geothermal Features in Limited Development, Research, Protected, and Small Geothermal Systems as a result of human activity.
7. No significant adverse effects on Significant Geothermal Features as a result of land use and the use of non-geothermal water.
8. No reduction in the life-supporting capacity and biodiversity or overall sustainability of Research and Protected Geothermal Systems as a result of human activity.
9. Adverse effects on other natural and physical resources including overlying structures (the built environment) avoided, remedied, or mitigated."

While there has been no formal quantitative assessment of the success of these Environmental Results Anticipated, it is fair to say that the existing geothermal policy has effectively almost halted most of the major adverse effects of development of geothermal resources and of land and water affecting geothermal resources, while not being able to turn the clock back on irreversible existing adverse effects.

## 8.2 Geothermal resources in the DPSIR framework

The adverse effects of geothermal resources of anthropogenic activity can be assessed in a DPSIR framework, and this has been done below, for the four major cause-and-effect dynamics acting on the Regional Geothermal Resource:

1) Effects of geothermal energy development on surface features and their dependent ecosystems
2) Effects of geothermal energy development on amount of energy and fluid available for future generations

3) Effects of geothermal development on other uses of surrounding land and water
4) Effects of land uses on geothermal surface features and their dependent ecosystems

The results are set out in Tables 11 to 14 below.

**Table 11: Effects of geothermal energy development on surface geothermal features and their dependent ecosystem**

| Item | Description | Examples |
|---|---|---|
| Drivers | The social, demographic and economic forces driving human activities that increase or mitigate pressures on the environment (e.g. economic and population growth). | • Economic and political forces driving demand for geothermally-sourced electricity and process heat. |
| Pressure | The stresses placed on the environment by human activities resulting from driving forces | • Large-scale fluid and energy extraction from geothermal reservoirs |
| State | The biophysical condition of the environment including its physical, chemical and biological characteristics, and how these characteristics are changing. | **Ecological**<br>• Fluid output of geothermal springs is depleted or rendered extinct<br>• Heat output of hot ground increased and expanded<br>• Thermophilic and extremophilic ecosystems stressed<br>• Weed incursion in geothermal areas<br>**Land use**<br>• More hydrothermal eruptions<br>• Greater slope instability in geothermally active areas |
| Impact | The ecological, economic, social and cultural consequences of changes in the state of the environment. | **Ecological**<br>• Species extinction or range reduction for some geothermal ecosystems<br>• Harbouring of invasive tropical exotic species<br>• Increase in terrestrial geothermal habitat.<br>**Cultural**<br>• Mahinga kai in geothermal water depleted<br>• Mauri of geothermal surface features depleted<br>• Number and experiential quality of tourism activities reduced<br>• Number and experiential quality of customary uses (bathing, cooking) reduced<br>**Land Use**<br>• More frequent landslides in geothermal areas causing damage to property and infrastructure including state highways, deaths, evacuations |
| Response | Societal responses to mitigate negative impacts on the environment and halt or reverse environmental damage. | **Policy**<br>• More effective application and enforcement of regional policy instruments regarding sustainable management of geothermal resources<br>• Stronger central and local government policy instruments developed to ensure sustainable management of geothermal resources<br>• Greater engagement between local government, tangata whenua, resource users, and researchers to sustainably manage the Regional Geothermal Resource.<br>**Science, Monitoring and education**<br>• More funding from central government and other sources for environmental research and mitigation. |

| Item | Description | Examples |
|---|---|---|
| | | • More environmental monitoring of the effects of geothermal resource use<br>• More planting, stock exclusion, weed control, animal and plant pest management and site rehabilitation of geothermal features<br>• Education targeted at geothermal resource users and the public regarding the rarity, vulnerability, and ecological importance of geothermal ecosystems. |

**Table 12: Effects of geothermal energy development on the amount of energy and fluid available for future generations**

| Item | Description | Examples |
|---|---|---|
| Drivers | The social, demographic and economic forces driving human activities that increase or mitigate pressures on the environment (e.g. economic and population growth). | • Economic and political forces driving demand for geothermally-sourced electricity and process heat. |
| Pressure | The stresses placed on the environment by human activities resulting from driving forces | • Large-scale energy extraction from finite geothermal reservoirs. |
| State | The physical, chemical and biological condition of the environment and how these characteristics are changing. | • Energy available in the accessible upper part of the geothermal reservoir is depleted at a rate faster than recharge. (Accessibility requires the zone to be within the drillable depth and the zone to be permeable.) |
| Impact | The ecological, economic, social and cultural consequences of changes in the state of the environment. | • More expensive energy<br>• Further reliance of fossil fuels<br>• Future generations do not have access to the same sustainable cheap energy resource |
| Response | Societal responses to mitigate negative impacts on the environment and halt or reverse environmental damage. | • Deeper drilling, which has the potential to provide some buffering of surface features from the effects of extraction.<br>• Development of methods for extracting heat from less permeable hot rock in the reservoir.<br>• Development of technology to exploit hotter more extreme zones.<br>• Stronger central and local policy instruments developed regarding sustainable use<br>• Existing environmental policies applied more rigorously<br>• Greater engagement between local government, tangata whenua, resource users, and researchers to sustainably manage the Regional Geothermal Resource.<br>• More use of fossil fuels<br>• Greater investment in existing renewable energy sources<br>• New sustainable technologies developed. |

**Table 13: Effects of geothermal development on other uses of surrounding land and water**

| Item | Description | Examples |
|---|---|---|
| Drivers | The social, demographic and economic forces driving human activities that increase or mitigate pressures on the environment (e.g. economic and population growth). | • Economic forces driving demand for geothermally-sourced electricity and process heat. |

| Item | Description | Examples |
|---|---|---|
| Pressure | The stresses placed on the environment by human activities resulting from driving forces e.g.<br>Effects of water pollution<br>Effects of habitat modification<br>Effects of land cover change<br>Erosion is a change in the state of the land and a pressure on freshwater and coastal habitats<br>Ocean acidification is a major impact of climate change, but it is also a change in the state of the ocean and a pressure on marine biodiversity. | • Large-scale energy and fluid extraction from geothermal reservoirs<br>• Associated infrastructure affecting other land users. |
| State | The physical, chemical and biological condition of the environment and how these characteristics are changing. | • Subsidence or inflation of land causing damage to buildings and infrastructure, inundation of land and infrastructure adjacent to waterways<br>• Heat output of geothermal ground increased<br>• Increased frequency of hydrothermal eruptions<br>• Greater slope instability on hot slopes<br>• Weed incursion on the margins of geothermal features<br>• Noise and vibration from drilling, well tests, station activities including fans and atmospheric discharges.<br>• Visual landscape alteration by infrastructure, steam discharge etc.<br>• Potential contamination of freshwater aquifers by injection of extracted geothermal fluid<br>• Depletion of freshwater aquifers by pressure drawdown into geothermal aquifer<br>• Potential contamination of surface water by discharge of used geothermal fluid. |
| Impact | The ecological, economic, social and cultural consequences of changes in the state of the environment. | • Costs associated with moving and repairing affected infrastructure such as roads and reticulated services.<br>• More frequent landslides in geothermal areas<br>• Mahinga kai in affected areas lost or depleted<br>• Mauri of affected areas lost or depleted<br>• More expensive sources of fresh water required |
| Response | Societal responses to mitigate negative impacts on the environment and halt or reverse environmental damage. | • Stronger central and local policy instruments developed regarding environmental effects of geothermal developments<br>• Existing environmental policies applied more rigorously<br>• Greater engagement between local government, tangata whenua, resource users, and researchers to sustainably manage the Regional Geothermal Resource.<br>• New sustainable technologies developed<br>• More monitoring of effects of geothermal development<br>• More planting, fencing, landscaping<br>• More central government and other funding for environmental research and mitigation. |

**Table 14: Effects of land uses on surface features and their dependent ecosystems**

| Item | Description | Examples |
|---|---|---|
| Drivers | The social, demographic and economic forces driving human activities that increase or mitigate pressures on the environment (e.g. economic and population growth). | • Economic forces driving urban development, changes in primary production of land and demand for geothermally-sourced electricity and process heat. |
| Pressure | The stresses placed on the environment by human activities resulting from driving forces | • Urban encroachment (subdivision, vandalism)<br>• Land-use changes (deforestation, dairy intensification)<br>• Incompatible land-use activities (weed spraying, vegetation pruning and clearance, soil disturbance) |
| State | The physical, chemical and biological condition of the environment and how these characteristics are changing. | • Thermophilic and extremophilic ecosystems subject to further stressors and potential destruction stressed<br>• Weed incursion in geothermal areas<br>• Geothermal features degraded, damaged or destroyed |
| Impact | The ecological, economic, social and cultural consequences of changes in the state of the environment. | • Species extinction or range reduction for some geothermal ecosystems<br>• Harbouring of invasive tropical exotic species<br>• Mahinga kai in geothermal water depleted<br>• Mauri of geothermal surface features reduced<br>• Number and experiential quality of tourism activities reduced<br>• Number and experiential quality of customary uses (bathing, cooking) reduced |
| Response | Societal responses to mitigate negative impacts on the environment and halt or reverse environmental damage. | • Stronger central and local policy instruments developed regarding environmental effects of geothermal developments<br>• Existing environmental policies applied more rigorously<br>• Greater engagement between local government, tangata whenua, resource users, and researchers to sustainably manage the Regional Geothermal Resource.<br>• New sustainable technologies developed<br>• More monitoring of effects of geothermal development<br>• More planting, fencing, landscaping<br>• More central government and other funding for environmental research and mitigation.<br>• More planting, stock exclusion, weed control, animal and plant pest management and site rehabilitation of geothermal features<br>• Education targeted at geothermal resource users and the public regarding the rarity, vulnerability, and ecological importance of geothermal ecosystems. |

# 9 Conclusion

The Waikato Regional Geothermal Resource provides many benefits to the regional community, the nation, and to investors in the companies that derive profits from use of the resource, such as electricity providers, primary producers, and tourism companies.

Prior to the enactment of the Resource Management Act 1991 (RMA) there was destruction and depletion of significant parts of the Regional Geothermal Resource. The resource is now largely protected, at least in law, by the RMA and regional policy instruments restricting or prohibiting adverse effects on surface geothermal features and ensuring that extractive uses are sustainable and from geothermal systems where adverse effects on surface geothermal features can be minimised. Nevertheless, increasing demands for this low-carbon energy source, and development pressures on the land surrounding geothermal surface features, lead to some adverse effects, whether consented or non-consented.

The subsurface geothermal resource lies largely hidden from us, extending many kilometres below our feet. Prospecting techniques such as deep drilling and remote sensing techniques such as magneto-tellurics are required to inform us about the nature and extent of the subsurface resource.

Surface geothermal features, and their dependent ecosystems are rare and vulnerable, and can be accidently or unintentionally exposed to adverse effects from human interaction.

We continue to learn more about the intricate nature of the Regional Geothermal Resource, the changing pressures that are placed on it, and the effects of those pressures. As socio-economic drivers such as the desire for electricity and intensifying land uses place pressure on the resource, the effects of those pressures need to be studied so that we can respond appropriately to ensure sustainable management and limit adverse effects. Lack of funding for monitoring and research severely impairs our ability to identify and respond to the threats.

# Bibliography


APR Consultants 1994. Tourism and its impacts on the Rotorua district economy. Prepared for the Rotorua District Council, Rotorua, March 1994.

Balane MOG, Luketina K, Zarrouk S, 2015. Lake Waikare low enthalpy geothermal resource, New Zealand: Initial field study. World Geothermal Congress 2015. Melbourne, Australia, International Geothermal Association.

Balane MOG, Luketina K, Zarrouk S, Mutonga MW 2016. Lake Waikare low enthalpy geothermal system, New Zealand. Hamilton, Waikato Regional Council. Unpublished report. WRC Document no. 3777506

Barns S, Luketina KM 2011. Valuing uses of the Waikato Regional geothermal resource Waikato Regional Council Technical Report 2011/15. Hamilton, Waikato Regional Council.

Bay of Plenty Regional Council. 1999. Rotorua Geothermal Management Plan. Whakatane, Bay of Plenty Regional Council.

Bolton RS 1998. Notes on the early history of Wairakei. In: Simmons SF, Morgan OE, Dunstall MG eds. Proceedings of the 20th New Zealand Geothermal Workshop 1998. Auckland, Geothermal Institute, University of Auckland. 13-20.

Brodnax R 2022 in press. Herpetofauna of geothermal ecosystems in the Waikato Region. Waikato Regional Council Technical Report 2022/07, Hamilton, Waikato Regional Council.

Catlin A, David B, Hamer M, Lake M, Luketina K, Özkundakci D, Reeves P, Smith J 2017. Water quality and biodiversity survey of three Waiotapu geothermal lakes. Proceedings of the 39th New Zealand Geothermal Workshop. Rotorua, New Zealand: The University of Auckland http://www.geothermal-energy.org/pdf/IGAstandard/NZGW/2017/041_Luketina-Final.pdf

Cheptum I, Luketina K 2015. Preliminary assessment of the low enthalpy geothermal system at Ohinewai, New Zealand. Proceedings of the World Geothermal Congress 2015. Melbourne, Australia, International Geothermal Association.

Chrzanowski S 1997. Hot and steamy: A gaze at tourists' evaluation of geothermal resources in the Waikato Region. Unpublished MSc thesis. Hamilton, Department of Geography, University of Waikato.

Cody AD 1993. Onekeneke Thermal Valley (De Brett's): A summary of available historical data. Unpublished report for Waikato Regional Council. WRC Document no. 4334281.

Cody AD 1995. Re: Waipahihi – Onekeneke: field notes. Unpublished report for Waikato Regional Council. WRC Document no 4223347.

Cody AD 1996. Monitoring and exception reporting on geothermal features in Waikato Region: Report for 1 July 1995 to 30 June 1996. Unpublished Report for Waikato Regional Council. WRC Document no. 644937.

Cody AD 1997. Monitoring and exception reporting on geothermal features in Waikato Region: Report for 1 July 1996 to 30 June 1997. Unpublished Report for Waikato Regional Council. WRC Document no. 3749624.

Cody AD 1999. Monitoring and exception reporting on geothermal features in Waikato Region: Report for 1 July 1998 to 30 June 1999. Unpublished Report for Waikato Regional Council. WRC Document no. 4108408.

Cody AD 2000. Monitoring and exception reporting on geothermal features in Waikato Region: Report for 1 July 1999 to 30 June 2000. Unpublished Report for Waikato Regional Council. WRC Document no. 863282.

Cody AD 2001. Monitoring and exception reporting on geothermal features in Waikato Region: Report for 1 July 2000 to 30 June 2001. Unpublished Report for Waikato Regional Council. WRC Document no. 4109344.

Cody AD 2002. Monitoring and exception reporting on geothermal features in Waikato Region: Report for 1 July 2001 to 30 June 2002. Unpublished Report for Waikato Regional Council. WRC Document no. 4109190.

Cody AD 2002b. Geyser and hot springs recordings, February 2002. Unpublished report for Waikato Regional Council. WRC Document no. 17401017.

Cody AD 2003. Monitoring and exception reporting on geothermal features in Waikato Region: Report for 1 July 2002 to 30 June 2003. Unpublished Report for Waikato Regional Council. WRC Document no. 4109858.

Cody AD 2004. Monitoring and exception reporting on geothermal features in Waikato Region: Report for 1 July 2003 to 30 June 2004. Unpublished Report for Waikato Regional Council. WRC Document no. 4057256.

Cody AD 2005. Monitoring and exception reporting on geothermal features in Waikato Region: Report for 1 July 2004 to 30 June 2005. Unpublished Report for Waikato Regional Council. WRC Document no. 1172964.

Cody AD 2007. Geodiversity of geothermal fields in the Taupō Volcanic Zone. DOC Research and Development Series 281. Wellington, Department of Conservation.

Cody, AD, Keam RF, Lebe J, Lynne B, Luketina K 2020. Sinter-forming springs and geysers of the Waikato region. Waikato Regional Council Technical Report 2020/04. Sinter-forming springs and geysers of the Waikato region | Waikato Regional Council

Curtis RJ 1988. Low temperature heat utilisation - Tauhara Geothermal Field, Taupo. Waikato Catchment Board Technical Report 1988/02. Hamilton, Waikato Catchment Board.

Denne T 2012. Environmental costs of electricity generation. Waikato Regional Council Technical Report 2007/09. Hamilton, Waikato Regional Council.

Department of Conservation 2000. The New Zealand biodiversity strategy. Wellington, Department of Conservation (DOC).

de Ronde C, Stoffers P, Garbe Schoenberg D, Christenson BW, Jones B, Manconi R, Browne PRL, Hissman K, Botz R, Davy BW, Schmitt M, Battershill CN 2002. Discovery of active hydrothermal venting in Lake Taupō, New Zealand. Journal of Volcanology and Geothermal Research 115: 257-275.

Duggan I, Boothroyd I 2001. The distribution of biota from some geothermally influenced waters in the Taupō Volcanic Zone. Waikato Regional Council Technical Report 2021/35. The distribution of biota from some geothermally influenced waters in the Taupō Volcanic Zone | Waikato Regional Council

Duggan I, Boothroyd I 2002. The distribution of biota from some geothermally influenced standing waters in the Taupō Volcanic Zone. Waikato Regional Council Technical Report 2021/36 The distribution of biota from some geothermally influenced standing waters in the Taupō Volcanic Zone | Waikato Regional Council

Environmental Reporting Act 2015. (No. 87).

Golder Associates Ltd 2013. REGEMP II 2013 interpretation of geochemical data. Waikato Regional Council Technical Report 2013/30. Hamilton, Waikato Regional Council.

Gong J, Munoz-Saez C, Wilmeth DT, Myers KD, Homann M, Arp G, Skok JR, Van Zuilen, MA 2022. Morphogenesis of digitate structures in hot spring silica sinters of the El Tatio geothermal field, Chile. Geobiology 20(1): 19.

Harvey M 2018a. Cloud-based photogrammetry processing of aerial imagery: Phase 2., Unpublished report for Waikato Regional Council. WRC Document no. 13283152.

Harvey M 2018b. Geothermal monitoring using remotely sensed data and cloud Computing. Proceedings 40th New Zealand Geothermal Workshop. Wairakei Resort, Taupo, 14-16 November 2018. 6 p.

Harvey M 2020. Uncrewed aerial vehicle and carbon dioxide flux surveys at Waikite, Gravesons Road and Ohaaki. Waikato Regional Council Internal Report 2015/49. Hamilton, Waikato Regional Council.

Harvey MC 2021. Sentinel-1 InSAR captures 2019 catastrophic White Island eruption. Journal of Volcanology and Geothermal Research 411. Article 107124.

Harvey MC, Luketina K 2015. Thermal infrared cameras and drones: A match made in heaven for cost-effective geothermal exploration, monitoring and development. Proceedings of the New Zealand Geothermal Workshop. Taupo, New Zealand. Geothermal Institute. Auckland, University of Auckland.

Harvey M, Harvey C, Rowland J, Luketina K 2016. Drones in geothermal exploration. Proceedings of the 6th African Rift Geothermal Conference. Addis Ababa, Ethiopia, United Nations Environment Programme.

Harvey MC, Rowland JV, Luketina KM. 2016. Drone with thermal infrared camera provides high resolution georeferenced imagery of the Waikite Geothermal Area, New Zealand. Journal of Volcanology and Geothermal Research 325: 61-69.

Harvey MC, Luketina KM, McLeod J, Rowland J 2018. Geothermal monitoring using remotely sensed data and cloud computing. Proceedings of the 40th New Zealand Geothermal Workshop. Taupo, New Zealand: Geothermal Institute, The University of Auckland.. File is ready (geothermal-energy.org)

Harvey M, McLeod J, Luketina K, Harvey C 2019. Geothermal subsidence and inflation in Taupo: A comparison of detection methods. Proceedings of the 41st New Zealand Geothermal Workshop. Auckland, New Zealand: The University of Auckland. https://www.geothermal-energy.org/pdf/IGAstandard/NZGW/2019/093.pdf

Harvey MC, McLeod J, Luketina K, Harvey C 2021. Detecting subsidence using remote sensing methods. Proceedings of the 2020 World Geothermal Congress. Reykjavik, Iceland, International Geothermal Association.

Hochstein MP, Nixon IM 1979. Geophysical study of the Hauraki depression, North Island, New Zealand. New Zealand Journal of Geology and Geophysics 22: 1-19.

Holwerda N, Blair I 2007. Mapping of geothermal streams and springs. Waikato Regional Council Technical Report 2007/10. Hamilton, Waikato Regional Council.

Huser B 2005. Environment Court evidence of Beat Huser on appeals on Proposed Change 1 to the Waikato Regional Policy Statement and Proposed Variation 2 to the Waikato Regional Plan. Hamilton, Waikato Regional Council. WRC document number 1161054.

Huser B, Jenkinson D 1996. Regional geothermal features monitoring programme. Waikato Regional Council Technical Report 96/18. Hamilton, Waikato Regional Council.

Ingham MR, Bibby HM, Heise W, Jones KA, Cairns P, Dravitzki S, Bennie SL, Caldwell TG, Ogawa Y 2009. A magnetotelluric study of Mount Ruapehu volcano, New Zealand. Geophysical Journal International 179(18) :887-904.

Keam RF, Luketina KM, Pipe LZ 2005. Definition and listing of significant geothermal feature types in the Waikato Region. Proceedings of the World Geothermal Congress 2005. Antalya, Turkey, International Geothermal Association.

King J 2015. Okauia and Hauraki Plains low enthalpy geothermal systems. Unpublished report for Waikato Regional Council. Document no. 3462767.

Lawless JV, Lovelock BG 2001. New Zealand's geothermal resource base. Proceedings of the New Zealand Geothermal Association Seminar. Taupō, New Zealand Geothermal Association.

Lebe JL 2022 in press. Tauhara Domestic Bores: Updating of geographical and hydrogeological information. Waikato Regional Council Technical Report 2021/16.

Ledingham P 1998. Geothermal energy. In: Cross B ed. The world directory of renewable energy: Suppliers and services 1998. London, James & James. 108-110.

Lloyd K, Beadel S, Smith D, Bycroft C, Bawden R, Harvey M, McLeod J, Luketina K 2016. Ground and aerial photography of geothermal vegetation at Craters of the Moon Geothermal Area, Waikato. Proceedings of the 37th New Zealand Geothermal Workshop, Auckland, New Zealand: The University of Auckland.

Local Government Act 2002. No. 84.

Luketina KM 2002. Numbers of visitors to geothermal attractions in the Waikato Region. Waikato Regional Council Technical Report 2002/05. Hamilton, Waikato Regional Council.

Luketina KM 2005. Environment Court rebuttal evidence of Katherine Luketina for Waikato Regional Council on appeals on Proposed Change 1 to the Waikato Regional Policy Statement and Proposed Variation 2 to the Waikato Regional Plan. Hamilton, Waikato Regional Council. Doc no. 1020832.

Luketina KM 2007. REGEMP II: Regional Geothermal Geochemistry Monitoring Programme. Waikato Regional Council Technical Report 2007/36. Hamilton, Waikato Regional Council. https://www.waikatoregion.govt.nz/services/publications/tr200736/

Luketina KM, Cody AD 2002. Summary of New Zealand geysers: Waikato Region outside of Rotorua, GOSA Transactions 7:169 – 182. Geyser Observation and Study Association, USA.

Luketina K, Yuafrinaldi Y, Zarrouk SJ 2015. Onekeneke Stream, Taupo: Historical changes and their causes. Proceedings of the New Zealand Geothermal Workshop. Auckland, New Zealand, The University of Auckland.

Luketina K, Olubode F, Phillips Y 2017. Valuing uses of the Waikato and Bay of Plenty Geothermal Resource. Proceedings of the 38th New Zealand Geothermal Workshop. Rotorua, New Zealand, The University of Auckland.

Lynne BY 2007a. Hydrothermal eruption craters within the Horohoro thermal area and Tauhara. Unpublished report for Waikato Regional Council. Document no. 1290411.

Lynne BY 2007b. Monitoring of geothermal features annual report 2007. Unpublished report for Waikato Regional Council. Document no. 1215501.

Lynne BY 2008. Monitoring of geothermal features annual report 2008. Unpublished report for Waikato Regional Council. Document no. 1341524.

Lynne BY 2009. Monitoring of geothermal features annual report 2009. Waikato Regional Council Technical Report 2009/25. Hamilton, Waikato Regional Council.

Lynne BY, Smith IJ, Smith GJ, Luketina K 2016. Imaging the shallow subsurface of Armstrong Reserve, Taupo, New Zealand, using ground penetrating radar. Proceedings of the New Zealand Geothermal Workshop, Auckland, New Zealand. Auckland, Geothermal Institute, The University of Auckland.

McDermott Fairgray Group Ltd, Hill Young Cooper Ltd 1996. Taupō visitor industry survey: prospects, issues, and future scenarios. Prepared for Taupō District Council, Taupō.

Ministry of Business Innovation and Employment 2021 [Energy in New Zealand | Ministry of Business, Innovation & Employment (mbie.govt.nz)] [accessed 7 March 2022].

Mongillo MA, Clelland L 1984. Concise listing of information on the thermal areas and thermal springs of New Zealand. New Zealand Department of Scientific and Industrial Research Geothermal Report no. 9. Wairakei, New Zealand, DSIR, Geothermal Coordination Group.

Moody K, Zarrouk S, Luketina K 2015. The Te Aroha low enthalpy geothermal system, New Zealand: Review and analysis. Hamilton, Waikato Regional Council. Document no. 3694550.

Moody K, Zarrouk S, Luketina K 2022 in press. The Te Aroha low enthalpy geothermal system, New Zealand: Review and analysis. Proceedings of the 44th New Zealand Geothermal Workshop. Auckland, University of Auckland.

Murgulov V, Luketina K, Zarrouk S 2016. Investigation of the geothermal signature of the Motuoapa Marina, Lake Taupo, New Zealand. Proceedings of the New Zealand Geothermal Workshop. Auckland, New Zealand, The University of Auckland.

Murithi LM 2013. The chemistry of waters of Te Aroha geothermal system. Waikato Regional Council Technical Report 2013/07. Hamilton, Waikato Regional Council.

Mutonga MW, Luketina K, Zarrouk SJ 2015. The Waitoa low enthalpy geothermal system, New Zealand. Proceedings of the New Zealand Geothermal Workshop. Taupo, New Zealand, The University of Auckland.

Newson J 2010. Geothermal features annual monitoring report, June 2010. Waikato Regional Council Technical Report 2010/30. Hamilton, Waikato Regional Council.

Newson J 2011. Geothermal features annual monitoring report, July 2011. Waikato Regional Council Technical Report 2012/11. Hamilton, Waikato Regional Council.

Newson J, McKibbin R 2015. Analysis of geothermal spring temperature time series from the Taupo Volcanic Zone, New Zealand. Waikato Regional Council Internal Series 2015/50. Hamilton, Waikato Regional Council.

Nikrou P, Newson J, McKibbin R, Luketina, K. 2013a. Geothermal spring temperature analysis. Proceedings of the New Zealand Geothermal Workshop. Rotorua, New Zealand, University of Auckland. http://www.geothermal-energy.org/pdf/IGAstandard/NZGW/2013/McKibbin_Final.pdf

Nikrou P, Newson J, McKibbin R 2013b. Time series analysis of selected geothermal spring temperature recordings. Waikato Regional Council Technical Report 2013/17. Hamilton, Waikato Regional Council.

NZGA New Zealand Geothermal Association 2022. Geothermal in New Zealand |Systems, Electricity and Uses (nzgeothermal.org.nz) [accessed 20 May 2022].

OECD 2001. OECD Environmental strategy for the first decade of the 21st century: Adopted by OECD Environment Ministers 16 May 2001. Paris, Organisation for Economic Co-operation and Development (OECD).

O'Sullivan M, Mannington W 2005. Renewability of the Wairakei-Tauhara Geothermal Resource. Proceedings of the World Geothermal Congress. International Geothermal Association, Antalya, Turkey.

Parkyn S, Boothroyd I 2000. Aquatic biota of geothermal ecosystems: Annotated bibliography of biodiversity, distribution and environmental significance. NIWA Client Report EVW01217 for Waikato Regional Council. Hamilton, National Institute of Water and Atmospheric Research (NIWA).

Parliamentary Commissioner for the Environment 2019. Focusing Aotearoa New Zealand’s environmental reporting system. Wellington, Parliamentary Commissioner for the Environment.

Peter AM, Luketina KM, Newson J 2012. Low enthalpy geothermal resources – Miranda-Kaiaua, New Zealand. Proceedings of the New Zealand Geothermal Workshop 2012. Auckland, New Zealand, University of Auckland. http://www.geothermal-energy.org/pdf/IGAstandard/NZGW/2012/46654final00033.pdf

Pope J, Christenson H 2022. Regional geothermal geochemistry review and interpretation. Report for Waikato Regional Council, Verum Group Report J000009 (in press). WRC doc number 24602703.

Power JF, Carere CR, Lee CK, Wakerley GLJ, Evans DW, Button M, White D, Climo MD, Hinze AM, Morgan XC, McDonald IR, Cary SC, Stott MB 2018. Microbial biogeography of 925 geothermal springs in New Zealand. Nature Communications 9(1): 2876.

Pritchett JW 1998. Modelling post-abandonment electrical capacity recovery for a two-phase geothermal reservoir. Geothermal Resources Council Transactions 22: 521-528.

Ramadhan Y, Zarrouk SJ, Luketina K 2017. Investigating the geothermal signature of the Kaimai Tunnel, New Zealand. 39th New Zealand Geothermal Workshop. Rotorua, New Zealand: The University of Auckland.

Resource Management Act 1991. No. 69.

Risk GF 2000a. Boundaries of Horomatangi, Tokaanu-Waihi-Hipaua, Waiotapu-Waikite-Waimangu and Atiamuri geothermal fields. Client Report 2000/22 for Waikato Regional Council. Taupo, Institute of Geological and Nuclear Sciences Ltd. (IGNS).

Risk GF 2000b. Boundaries of Horohoro, Te Kopia, Orakei Korako, Ngatamariki and Reporoa geothermal fields. Client Report 2000/131 for Waikato Regional Council. Taupo, Institute of Geological and Nuclear Sciences Ltd. (IGNS).

Risk GF 2003. Boundary of Tongariro geothermal systems. IGNS Client Report 2000/144 for Waikato Regional Council. Taupo, Institute of Geological and Nuclear Sciences Ltd. (IGNS).

Rustandi D, Zarrouk SJ, Luketina KM. 2016. The Mangakino geothermal system. New Zealand Geothermal Workshop. Auckland, New Zealand, The University of Auckland.

Rybach L, Megel T, Eugster WJ 2000. At what time scale are geothermal resources renewable. World Geothermal Congress. Kyushu and Tohuku, Japan, International Geothermal Association.

Sinclair Knight Merz 2002. Resource capacity estimates for high temperature geothermal systems in the Waikato Region. Waikato Regional Council Technical Report 2002/22. Hamilton, Waikato Regional Council.

Stefansson V 2000. The renewability of geothermal energy. World Geothermal Congress. 883-888.

Stevens MI, Cody AD, Hogg ID 2003. Habitat characteristics of geothermally influenced waters in the Waikato. CBER Consultancy Report no. 25 for Waikato Regional Council. Hamilton, University of Waikato. Centre for Biodiversity and Ecology Research (CBER).

Thain IA 2003. Briefing paper on hot dry rock and enhanced geothermal systems: a report for Waikato Regional Council. Taupō, Geothermal and Energy Technical Services Ltd.

Turk J, Luketina K 2018. Insights into the chemistry of waters beyond the Te Aroha Domain. 40th New Zealand Geothermal Workshop. Taupo, New Zealand, The University of Auckland.

UNCED 1992. United Nations Conference on Environment and Development (Agenda 21), 3 – 14 June 1992, Rio De Janeiro, Brazil.

UNECE 2017. Application of the United Nations Framework Classification for Resources (UNFC) to Geothermal Energy Resources: Selected case studies. p 83. Information Service, United Nations Economic Commission for Europe.

van Campen B, Archer RA, Grinlinton D 2019. Ohaaki Resource Assessment in UNFC Framework and Proposal. 41st New Zealand Geothermal Workshop. University of Auckland, Auckland.

Waikato Regional Council 1998. Waikato State of the Environment Report. Hamilton, Waikato Regional Council.

Waikato Regional Council 2012. Waikato Regional Plan: (Reprinted April 2012 – incorporating Variations No.2, No.5, No. 6 and No.7). Waikato Regional Council Policy Series 2007/21. Hamilton, Waikato Regional Council.

Waikato Regional Council 2016. Waikato Regional Policy Statement. Waikato Regional Council Policy Series 2016/01. Hamilton, Waikato Regional Council.

Webster-Brown JG, Brown KL 2008. Interpretation of geochemical data (REGEMP II) and recommendations for further monitoring. Waikato Regional Council Technical Report 2008/01. Hamilton, Waikato Regional Council.

Webster-Brown JG, Brown KL 2010. Interpretation of geochemical data (REGEMP II) and recommendations for further monitoring. Waikato Regional Council Technical Report 2012/07. Hamilton, Waikato Regional Council.

Wildland Consultants 2000. Geothermal vegetation of the Waikato Region. Wildland Consultants Ltd Contract Report No. 297 prepared for Waikato Regional Council.

Wildland Consultants 2003. Geothermal vegetation of the Waikato Region - Revised and expanded 2003. Wildland Consultants Ltd Contract Report No. 664 prepared for Environment Waikato (Waikato Regional Council).

Wildland Consultants 2004. Geothermal vegetation of the Waikato Region - Revised 2004. Wildland Consultants Ltd Contract Report No. 896 prepared for Environment Waikato (Waikato Regional Council).

Wildland Consultants Ltd 2011. Geothermal vegetation of the Waikato Region: An update based on 2007 aerial photographs. Waikato Regional Council Technical Report 2011/29. Hamilton, Waikato Regional Council.

Wildland Consultants Ltd 2011a. Priorities for pest plant control, pest animal control, and fencing at geothermal sites in the Waikato Region: 2011 Update. Waikato Regional Council Technical Report 2011/28. Hamilton, Waikato Regional Council. I don't know why these two are yellow?

Wildland Consultants 2011b. Ranking of sites with geothermal vegetation and habitats for biodiversity management in the Waikato Region. Wildland Consultants Ltd Contract Report No. 2756 prepared for Waikato Regional Council.

Wildland Consultants 2014. Ranking of geothermal ecosystems for biodiversity management in the Waikato Region. Wildland Consultants Ltd Contract Report No. 2756a prepared for Waikato Regional Council.

Wildland Consultants 2014a. Geothermal vegetation of the Waikato Region, 2014. Wildland Consultants Contract Report No. 3330 prepared for Waikato Regional Council.

Wildland Consultants 2016. Application of ecological indicators for the extent, condition, and protection level of geothermal habitats, Waikato Region. Wildland Consultants Ltd Contract Report No. 3504b prepared for Waikato Regional Council.

Wildland Consultants 2018. Desktop assessment of selected ecosystem services provided by terrestrial geothermal sites in the Waikato Region. Waikato Regional Council Technical Report 2018/27. Hamilton, Waikato Regional Council. Desktop assessment of selected ecosystem services provided by terrestrial geothermal sites in the Waikato Region | Waikato Regional Council

Wildland Consultants 2021. Geothermal vegetation of the Waikato Region, 2021 update: Thirteen sites including all sites in Wairakei-Tauhara Geothermal System. Wildland Consultants Ltd Contract Report No. 5483 prepared for Waikato Regional Council.

Willoughby B, Blakemore R 2012. Soil macro-fauna in geothermal heated soils in the Waikato Region. Waikato Regional Council Technical Report 2012/29. Hamilton, Waikato Regional Council.

Willoughby B, Beard C 2013. Invertebrate macro-fauna in geothermal soil under native vegetation in the Waikato Region. Waikato Regional Council Technical Report 2013/32. Hamilton, Waikato Regional Council.

Willoughby B, Beard C 2015. GEORGA: Managing biodiversity in geothermal sites. Waikato Regional Council Technical Report 2015/17. Hamilton, Waikato Regional Council.

Wilson N 2019. REGEMP II: 2018 interpretation of geochemical data. REGEMP II. Waikato Regional Council Technical Report 2019/05. Hamilton, Waikato Regional Council.