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REGIONAL COUNCIL
Te Kaunihera ā Rohe o Waikato

Definition and listing of significant geothermal feature types

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Jesse Lebe very ably picked up the project after it had been neglected for lack of time for some years and completed the amendments that the authors had agreed upon. He also incorporated many useful photographs.

This report is dedicated to the memory of Emeritus Associate Professor Ronald F Keam of the Physics Dept, The University of Auckland, the principal author, who passed away on 6 February 2019. Ron was one of the greatest giants of the New Zealand geothermal science community.

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1 Introduction

1.1 Purpose of this report

Geothermal manifestations on such a scale as occurs in New Zealand are rare in the global context. And within New Zealand, most of the nation's geothermal resource is concentrated within the Waikato Region.

The management of that resource has been identified as an important function for the Waikato Regional Council, which under the Resource Management Act 1991 (the RMA) has functions, powers, and duties in respect of the sustainable management of the regional geothermal resource. Through its Regional Policy Statement and Regional Plan, Council seeks to ensure a careful balance between often-competing interests in geothermal resources, including, where deemed necessary, the interest that certain elements be preserved in as nearly a pristine state as possible.

This document has been prepared by Council as part of its ongoing monitoring and assessment of geothermal manifestations in the Waikato Region. It is produced in conformity with the RMA Section 35 requirement to describe the state of the environment. It is intended to be an integral part of the background for the geothermal policy being developed by Council.

Although geothermal manifestations occur not only in the Waikato Region, but also elsewhere in New Zealand (and other parts of the world), Waikato Regional Council's primary responsibilities apply to its own region, so that the document focuses on occurrences within the region. Nevertheless, it is hoped that the following material will be helpful to those responsible for similar considerations elsewhere.

Assessment of a geothermal resource is a complex task. The most complete assessment would be performed at several scales – global, national, regional, local, and by thermal area. (Geothermal manifestations usually occur in localised concentrations of surface features generally termed *geothermal fields* or *geothermal areas* or, simply, *thermal areas*). However, that is beyond the scope of the purposes of this report, which has been defined as being to undertake an assessment in terms of geothermal feature types. This will be performed by defining those types and then assessing the degree to which they require special efforts at protection based on considerations of rarity and vulnerability.

1.2 The regional geothermal resource

The regional geothermal resource includes all geothermal energy (including geothermal water), 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 energy, located in the Region. This resource occurs throughout the Waikato Region, although its surface expression is most concentrated in the Taupo and Rotorua areas (see Figure 1.1 on page 7).

The regional geothermal resource is divided by natural processes into distinct "geothermal systems". A "geothermal system" is a connected region of the Earth where the rock by natural processes has been raised to an elevated temperature with respect to contiguous regions. A "hydrothermal system" is a geothermal system with significant proportions of fluid, largely water substance in either or both of its relevant phases (liquid water and steam) and where the rock is sufficiently permeable for much of the fluid to be mobile or potential mobile. Since all the known geothermal systems in New Zealand are hydrothermal systems, the terms are interchangeable, and since the term "geothermal system" is the one most widely used, this document uses that term throughout. Because geothermal fluid is mineralised it is significantly more electrically conductive than fresh meteoric water and the boundary of a system can be determined by measurements of electrical conductivity (or, equivalently, its inverse, electrical resistivity).

Each geothermal system comprises sets of one or more contiguous upflow systems where fluid rises from depth as a buoyant plume of hot water, steam and gases, and usually emerges at the Earth's surface in a reasonably well-defined area of geothermal discharge features. Such separate upflows are termed "geothermal fields", and if there is more than one within a system, they are in almost all cases linked to each other by sub-surface lateral flow. A geothermal system may support an isolated hot spring, a group of surface features, or several groups of features. Alternatively, there may be no visible expression at the surface. Where there is only one upflow in a system, the terms "field" and "system" are interchangeable.

At greater depths, it is accepted that there is a common heat source, something recognised from early times in Maori narrative regarding the origin of the geothermal resource. In some cases, there is doubt over the near-surface hydrological separation between neighbouring geothermal systems.

A geothermal system is *high temperature* if its water substance is either two phase, or contains liquid water that would boil if it were brought to the surface at the temperature it possesses.[1] A geothermal system is *low temperature* if it holds liquid water alone and at temperatures such that it would not boil if brought to the surface.

There is a clear distinction between the region's high temperature geothermal systems and its low temperature geothermal systems. The high temperature systems are all found within or adjacent to the active volcanic band known as the Taupo Volcanic Zone (TVZ) stretching from Mt Ruapehu to White Island (Whakaari) and beyond. These systems cover a large area, and contain large volumes of heated rock and geothermal fluid of temperatures of up to 350 °C. The low temperature geothermal systems are scattered throughout the region, including the Central Volcanic Region. They generally produce water of less than 100 °C and are small in area and volume of water discharged.

Because of the clear difference in size between high temperature and low temperature systems, for brevity, high temperatures systems are referred to in this document as "large geothermal systems" while low temperature systems are referred to as "small geothermal systems".

The Resource Management Act 1991 states:

> ""Geothermal water" means water heated within the earth by natural phenomena to a temperature of 30 degrees Celsius or more; and includes all steam, water, and water vapour, and every mixture of all or any of them that has been heated by natural phenomena".

This provides a convenient definition of the lower bound of temperature for geothermal water, and our analysis takes that definition into account.

Both the deeper, single phase (liquid water) parts of high temperature systems and all parts of low temperature systems, working by convective movements of deeply circulating meteoric water, possess long-term stable upflows, for time scales of 10^3 to 10^6 years. This of course

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[1]High temperature steam-dominated systems, which are almost single phase, nevertheless must have liquid water at great depth, and usually there is also some liquid water to be found as condensate at shallow depths.

presupposes the systems are not subjected to major external perturbations such as might be produced by local epicentre large magnitude earthquakes or local large volcanic eruptions.[2]

But even though the deep upflow in high temperature systems is almost steady, the presence of both water phases (steam and water) within the host rock in the upper regions can cause the near-surface activities of discharging systems to vary greatly, and actual surface outflows sometimes change by considerable factors. What is happening is that fluid storage changes – with water sometimes replacing steam or vice versa – and diversions of the water flow and steam flow paths often occur. Changes in invisible subsurface outflows into streams and lakes are also usually undetected.

1.3 History of assessment of New Zealand's geothermal resources

The present document has precursors in several papers prepared over the past two and a half decades, and a brief summary of their approaches and results is now presented.

The first publication that attempted to assess relative values of New Zealand hydrothermal systems was the April 1980 report "*The preservation of hydrothermal system features of scientific and other interest*" by B.F. Houghton, E.F. Lloyd and R.F. Keam. This arose from a request by the Nature Conservation Council in response to concerns that geothermal fluid extraction in the Rainbow Mountain area might affect the natural activities of nearby geothermal features.[3]

This report considered the types of geothermal surface features that were present in the various New Zealand geothermal fields and classified those fields into proposed preservation categories. The classification methodology adopted was spelt out in the report together with some caveats. While the authors recognised (and listed) many values of hydrothermal systems, they acknowledged paying attention "…dominantly to scientific values, and indeed largely to geological / geophysical values, but with consideration being given to the other(s)."

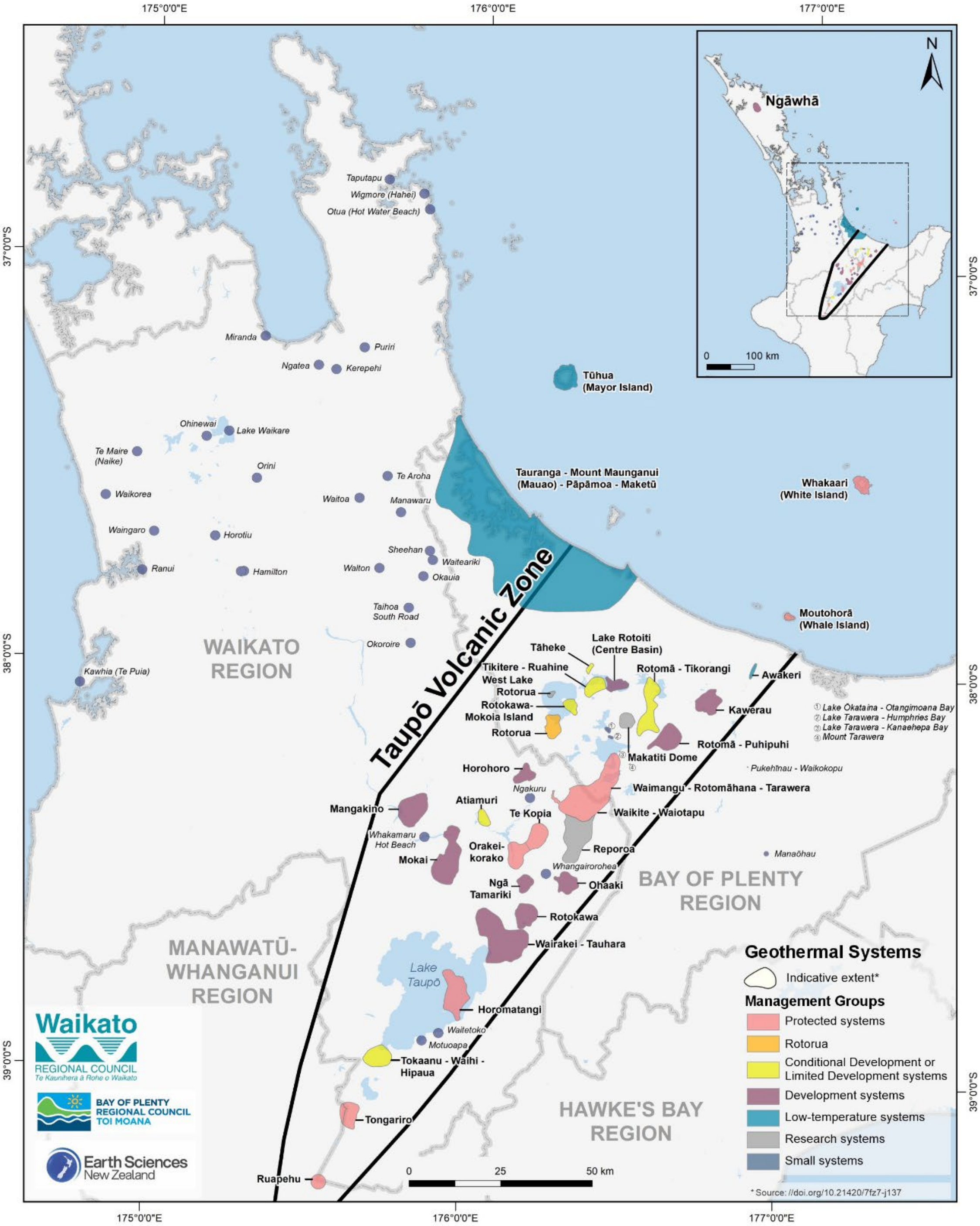
The next reports were those prepared at different times by David Given, in response to requests by the Waikato Catchment Board and its successor organisation, Waikato Regional Council. These documents emphasised biological (dominantly botanical) aspects of geothermal fields and Thus, remedied some limitations of the HLK report but were confined to considering fields in the Waikato Region. The first (Given, 1989) considered geothermal fields in the North Taupo area extending from Tauhara to Orakei Korako and Golden Springs. In this work the author provided an important summary of the nature of *value systems* before applying such general ideas to geothermal systems and then specifically to their botanical values (loc. cit. pp.56 – 63). The second report (Given, 1995), prepared subsequent to the passing of the Resource Management Act 1991, evaluated the relative significance of thirteen geothermal fields by summing, for each field, scores for various qualities. For each geothermal field two sums were explicitly presented: (1) for biological qualities and (2) for overall qualities. The third report (Given, 1996) integrated the results of the earlier ones and included assessments for all geothermal sites known in the Waikato Region. Although several qualities such as scientific interest and educational value were included in the assessments, there was otherwise no specific consideration given to the relative importance of geothermal features, so the emphasis was complementary to that of the Houghton *et al.* 1980 report.

[2] The Rotomahana / Waimangu system's total upflow was probably not affected to any great extent by the 1886 eruption, although surface activity changes have been dramatic and permanent. (Simmons *et al.*, 1993)

[3] And such concerns were well-founded considering the effects that water and steam extraction at Wairakei had already had on hot springs and geysers there.

It had become clear from before the time of the Houghton *et al.* report that more attention should be paid to the New Zealand geothermal resources. This is most dramatically illustrated in terms of the state by 1980 of those iconic symbols of hydrothermal activity, the geysers. Probably there had been something like two hundred geysers, small and large, in New Zealand in the nineteenth century. The 1886 volcanic eruption at Tarawera and Rotomahana destroyed the surface features at the latter place with the loss of perhaps a half dozen geysers. The formation of Lake Ohakuri behind the Ohakuri dam in 1961 drowned more than half of the surface features at Orakei Korako including three-quarters of the ninety-three geysers that had been counted there before that event. At around the same time all the geysers in Geyser Valley, Wairakei, and at The Spa ceased action as geothermal water pressures declined following the establishment of the Wairakei power station. By 1980 the proliferation of shallow geothermal bores supplying heat and mineral water for domestic use in Rotorua city began to affect the Whakarewarewa geysers seriously and there was a real chance that some of New Zealand's premier tourist attractions would be lost. Indeed, a count of the larger geysers showed that only about 15 then remained active in the country and that most of these were at Whakarewarewa. Publicity surrounding this decline and several court cases alerted people to the fragility and vulnerability of geothermal systems, and there has since been intervention by Government and by regional and local bodies. But there have been other losses as well: sinter formations have been severely damaged at Wairakei Geyser Valley, geothermal habitats have been significantly affected by weed encroachment (including self-sown pines). Many aspects of geothermal systems are Thus, at risk, and it is the responsibility and one of the tasks of Waikato Regional Council to manage the extent and variety of the regional geothermal resource to ensure protection of those parts of the resource that are most rare and most vulnerable.

Figure 1.1 Map of Geothermal Resources of the Upper North Island



2 Geothermal surface features

A geothermal feature is a manifestation at the surface of the Earth of geothermal processes. It may be the site of a discharge of steam, heated water, or a combination of both. Or it may be a land formation produced by geothermal processes, such as a hydrothermal eruption crater. Some types of features remain in existence after the fluid supply has ceased.

2.1 Attributes of geothermal features

A geothermal feature may possess, produce, or exhibit one or several of the following:

1) **Surface discharges:** An outflow of heat with any combination of steam, water, gases, and minerals in solution
2) **Fluid Products**:
    a) Flowing or standing bodies of water whose origin is either entirely or partly geothermal
    b) Clouds of condensate ("steam" clouds)
    c) Concentrations in the air of sulphur gases (H_2S and/or SO_2), which can produce distinctive odours
    d) Concentrations in the air of other gases including CO_2, mercury vapour, and methane
3) **Time-dependent behaviours**:
    a) Intermittency of surface discharge as in geysers and some flowing springs
    b) Fluctuating surface discharge as in some spouting springs (perpetual spouters), some fumaroles, and some flowing springs
    c) Infrequent or single eruptions such as hydrothermal eruptions and mud eruptions
4) **Steady-state behaviour:** Constancy of some springs, some spouting springs and mud pool activity
5) **Mineral Depositions**:
    a) Deposition of sinters from solution, usually silica or calcium carbonate (travertine)
    b) Deposition of sublimates from gases, dominantly sulphur crystals
    c) Production of efflorescences, largely sulphates
6) **Depositional Geomorphological features**:
    a) sinter aprons, cones, terraces, basins, stalactites, nodules, geyser eggs, patterned sinter surfaces
    b) mud volcanoes, mud flows, concentric mud ring patterns
7) **Non-depositional Geomorphological features:** Hydrothermal eruption craters, geothermal collapse pits and associated caves
8) **Altered Ground:** heated or chemically altered ground, including mud, and the processes that produce it
9) **Associated Distinctive Ecosystems**:
    a) Terrestrial geothermal ecosystems influenced by heat, humidity, and gases
    b) Standing geothermal water ecosystems influenced by heat and water chemistry
    c) Flowing geothermal water ecosystems influenced by heat, water chemistry, and flow
    d) Unusual and possibly unique microbiological assemblages: algae, bacteria, thermophiles, extremophiles
10) **Abstract attributes**:
    a) Cultural
    b) Historical
    c) Economic
    d) Aesthetic
    e) Recreational
    f) Educational
    g) Scientific

h) Intrinsic[4]

2.2 Definitions of geothermal surface features

The types of geothermal features that exist in the Waikato Region are described and defined in this section. There are three aims to be accomplished: the first is to identify clearly the types of feature; the second is to describe them according to the geothermal processes that create and sustain them; and the third is to define the “area” of each type of feature in order to provide certainty as to what we regard as being its surface boundary. The set of features of a particular type may be a subset of the set of features of a more inclusive type. For example, most geysers are also “Springs vigorously depositing sinter”, which in turn are also “geothermal springs and seeps”.

In most cases the definitions are self-explanatory; however, in other cases we have included after this subsection further information regarding particular feature types.

Steam-dominated features:

Figure 2.1 Multiple fumaroles at Karapiti. Copyright Katherine Luketina.

- **Fumarole:** Any naturally occurring vent, including those found underwater, whose main discharge consists of steam at the local boiling temperature of water, together, usually, with other gases of geothermal origin. The area of a fumarole comprises that 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.
- **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 superheated fumarole comprises that 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.
- **Geothermally heated ground or steaming ground:** Any naturally occurring area of ground whose temperature is raised by hydrothermal processes above neighbouring ambient ground temperature. The area of an occurrence of steaming or hot ground comprises that of all contiguous ground that is so heated together with the ground occupied by any distinctive ecosystem that extends outwards from the heated ground.
- **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.
- **Mud volcano:** A naturally occurring truncated cone of mud formed by the gas and steam discharges through some mud-pools when the mud has moderately high to high viscosity.
- **Mud geyser:** Any naturally occurring geothermally heated mud pool that occasionally or frequently erupts. The eruption produces an

Figure 2.2 Mud pool at Te Kopia.

[4] The RMA defines intrinsic values thus: “``Intrinsic values'', in relation to ecosystems, means those aspects of ecosystems and their constituent parts which have value in their own right, including—
(a)Their biological and genetic diversity; and
(b)The essential characteristics that determine an ecosystem's integrity, form, functioning, and resilience:”

intermittent or continuous discharge caused by the evolution of a phase dominated by steam or other gases. This must be vigorous enough forcefully to 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 comprises that of the mud pool, its banks, and any mud formations built up by the ejection of mud from the pool.

Remnant steam-dominated features:

- **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. Usually identifiable by the occurrence of hydrothermal breccia. The area of a hydrothermal eruption crater comprises that of the crater, its sides, and the ejecta of ash and pumiceous materials deposited around the crater.

Figure 2.3 Ngatamariki Main Pool, a hydrothermal eruption crater.

- **Geothermally altered ground:** Any naturally occurring area of ground whose chemical composition and structure has been significantly altered by geothermal steam and gases. The area of geothermally altered ground comprises that of all interconnected altered ground in a single occurrence and the land formation underlying or overlying it.
- **Geothermal collapse pit:** A naturally occurring pit or basin formed by collapse of earth as a consequence of the slow attack and weakening of the host rock by gases of geothermal origin. The area of a geothermal collapse pit comprises that of the pit and its sides and any visible associated caves.

Figure 2.4 Collapse pit at Waiotapu.

Geothermal water-dominated features:

- **Geothermal spring or seep:** Any natural spring producing water that has been heated by geothermal processes to a temperature of more than 30°C. The area of a hot spring comprises that of the spring basin, together with the area covered by any surface water composed of the undiluted outflow from its pool and any mineral deposits resulting from that outflow.
- **Spring vigorously depositing sinter:** Any naturally occurring geothermal spring that vigorously deposits sinter on surfaces covered by its outflow, or any artificially 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.
- **Unsubmerged spring vigorously depositing sinter:** Any naturally occurring unsubmerged geothermal spring that vigorously deposits sinter on surfaces covered by its outflow. The area of an unsubmerged sinter-depositing spring 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.

- **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. Allied geothermal features are spouting springs, soda geysers, and crypto-geysers. (See the next entries for details.) 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.
- **Spouting spring or perpetual spouter:** A naturally occurring geyser-like boiling spring whose eruption is continuous rather than intermittent.
- **Soda geyser:** A naturally occurring geyser-like feature whose erupting stage is driven mainly by the discharge of carbon dioxide rather than steam.
- **Crypto-geyser:** A naturally occurring intermittently discharging geothermal feature whose visible discharge is single phase (steam or water) and which does not project columns or jets of water above a static water level. Steam type crypto-geysers are subterranean geysers; water type crypto-geysers are submerged geysers.
- **Non-sinter-depositing geyser:** A naturally occurring geyser hosted by a steam-dominated geothermal system. Its liquid discharge consists of condensate and/or fresh meteoric water that has accumulated above up-flowing steam in the feeding channel(s).
- **Molten sulphur producing spring:** A naturally occurring 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.[5]

Figure 2.5 Oyster Pool, a spring at Waiotapu. Copyright Jesse Lebe.

Figure 2.6 An actively spouting spring at Waimangu. Copyright Jesse Lebe.

Figure 2.7 Sinter deposition at South Spring, Reporoa. Copyright Shaun Barnett.

Figure 2.8 Lady Knox Geyser at Waiotapu geysering.

[5] •Only three examples are known to us and have been seen by us, two in New Zealand and one in the United States.

Remnant geothermal water-dominated features:

- **Recent sinter:** any naturally occurring 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. (See also Section 2.5 below)
- **Ancient sinter:** any sinter body that has not received natural sinter deposition since before 1900. This includes carbonate sinters (travertine). The area of an ancient sinter body consists of that of all interconnected sinter in a single occurrence and the land formation underlying or overlying it.

Biological type geothermal features.

- **Significant geothermal terrestrial habitat:** Any naturally occurring area classified as being of International, National, Regional or District significance in the document "Geothermal Vegetation of the Waikato Region – Revised 2004", dated August 2004, prepared by Wildland Consultants Ltd for Waikato Regional Council, or any part of a geothermal area that meets the criteria for determining significant indigenous vegetation or significant habitat of indigenous fauna in Appendix 3 of the Waikato Regional Policy Statement. (See also Section 2.3 below).
- **Geothermal wetland, lake, pool, or stream:** Any naturally occurring wetland, lake, pool, or stream, whose chemical or temperature profile is so influenced by natural geothermal input that it either provides habitat for thermotolerant, thermophilic, or extremophilic organisms, or contains water whose temperature is 30°C or more. The area covered by a geothermal wetland, lake, pool, or stream consists of the geothermally part of the water body, the bed and banks of the geothermally part of the water body, any geothermal mineral deposits derived from the water body or its outflow, and any thermotolerant, thermophilic, or extremophilic ecosystems dependent on it.

Figure 2.9 Lycopodium at Te Kopia, a species that preferentiallly grows in geothermal habitats. Copyright Pete Corson.

Figure 2.10 A geothermal wetland surrounding the Otumuheke Stream.

NOTE: In the definitions above of non-biological type geothermal features, we have regarded any ecosystem dependent on a single feature as being part of that feature and its area is to be included in the "area" of that feature. To avoid ambiguity, we Thus, regard only such parts of an ecosystem as are not supported by single features as comprising a geothermal wetland, lake, pool, or stream. In other words, only an ecosystem supported by the discharges of more than one feature is regarded as qualifying for separate identity as a geothermal wetland, lake, pool, or stream.

2.3 Springs vigorously depositing sinter

Almost all geothermal springs are mineralised to some extent. There is a continuum between the amount of deposition that any spring is capable of, from no deposition to heavy deposition, depending mainly on the nature and degree of the mineralisation. The springs that readily deposit a heavy load of sinter that forms large expanses and unusual shapes are heavily mineralised, indicating that the main component of their water comes directly from the deep, hot part of the geothermal system. Such springs are relatively rare and sufficiently different from geothermal springs that form little or no sinter to warrant a separate status as a feature type.

2.4 Recent sinters, artificially submerged springs, and other 'lost' features

One major natural event since European settlement in New Zealand caused the loss of a substantial number of geothermal features. This was the 10 June 1886 "Tarawera" basaltic eruption that triggered a gigantic series of hydrothermal eruptions in the Rotomahana geothermal system. Among the features destroyed were the incomparable Te Tarata and Otukapuarangi, respectively the White and Pink Terraces. But in fact, none of the pre-existing surface features at Rotomahana survived. From published maps one can estimate that about 5 geysers were lost (Te Tarata, Ngahapu, Ngahutu, Koingo, Whatapoho), 1 possible mud geyser (Whakataratara), and around 50 flowing springs (mostly boiling), together with a dozen or so mud volcanoes, at least one super-heated fumarole (Whio, and possibly Te Rangi Pakaru), and many small non-superheated fumaroles. Ten to twelve hydrothermal eruption craters were destroyed, and large tracts of steaming ground disappeared, together with comparably-sized tracts of geothermal vegetation - which no doubt would have qualified for classification as Significant Geothermal Terrestrial Habitat features had they still been in existence. Some of the environs of the pre-eruption lake would have qualified as a geothermal wetland, and the lake itself would only marginally not have qualified as being a geothermal lake (since its temperature was about fifteen Celsius degrees above ambient (Hochstetter, 1959, page 153)), and it probably did not have sufficient mineral load for it to qualify as a geothermal habitat. A decaying sinter sheet floored part of the Waikanapanapa valley. On this were several collapse pits and/or the basins of extinct springs. These too disappeared in the eruption.

After the eruption the Rotomahana hydrothermal system developed alternative outlets for its fluids, using pathways created by the outbreak, so the lost features have been replaced by others. However, these comprise a different distribution of types. They now form the attractions of Waimangu and along the western shoreline of present-day Rotomahana.

While the paragraphs above describe a geothermal system outside the Waikato Region, it is mentioned because it was responsible for the loss of some outstanding New Zealand surface geothermal features.

In the Waikato Region the losses that have occurred have almost entirely been a result of human activity.

The most direct and comprehensive destruction has occurred in the Wairakei-Tauhara geothermal system. All geysers and all other springs that vigorously deposited sinter no longer flow, although their vents in some cases are now the sites of steam discharges. This has meant the loss of 29 geysers and 190 boiling springs at Wairakei Geyser Valley, about 6 hot and boiling springs in the Waiora Valley, 4 geysers at The Spa, and about 40 substantial springs that were not geysers there and in the general Tauhara area. New steam-dominated discharge features have proliferated, especially in the Karapiti area (including the Department of Conservation-administered tourist facility "Craters of the Moon"), because of the human intervention. Most springs producing mixed waters still flow, including at Waipahihi, Otumuheke, and Hall of Fame Stream, although some of these have also dried up, most notably the Kathleen Spring and AC Spring at Tauhara which once fed the AC Baths. The baths are now fed solely by bores.

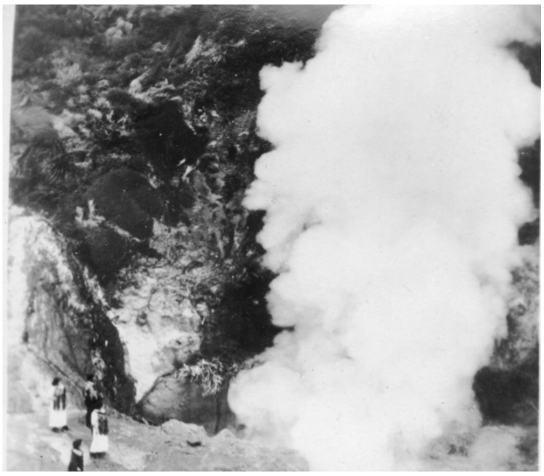


Figure 2.11 The Great Wairakei Geyser in 1929, one of many surface features that has been adversely affected by fluid extraction. Copyright B. Dickie.

At Ohaaki natural discharges have ceased from all (about 10) springs (although bore water is diverted through the old Ohaaki Ngawha (Ohaaki Pool) in order artificially to maintain the flow out of the ngawha. However, the flow out of the ngawha is channelled to some nearby baths and is Therefore, prevented from maintaining sinter deposition on the great sinter sheet that extends from the Ngawha down towards the Waikato River (which here forms the upper reaches of Lake Ohakuri).

At Rotokawa (which in earlier literature is spelt Rotokaua), the area has been essentially taken over and modified for the wells to supply the geothermal power station there. Since the start of operations, the outflow of the Parariki Stream has doubled, in terms of both water and chloride mass (K. Luketina, pers. comm).

At Mokai and most of Rotokawa apart from the springs around the lake, the natural surface features were mostly steam-dominated. For that reason, the effects of large-scale fluid extraction have been less pronounced, and, in any case, extraction commenced comparatively recently, in the late 1990s. At both locations full reinjection of extracted fluid is practised, which helps to limit extraction-induced decline in reservoir pressures and as a result surface flows are less affected, although at Rotokawa it appears that they may have increased.

At Orakei Korako about half of the approximately 1000 features mapped (including three quarters of the geysers) have been inundated by the waters of Ohakuri Lake following the construction of Ohakuri dam and the filling of Ohakuri lake in January 1961. The activities of a few of the springs remaining above lake level increased. Unlike the situation at geothermal systems where large-scale extraction occurs, the submerged features would no doubt largely recover if the lake were

Figure 2.12 Lake Ohakuri with the main sinter terraces in the background. Copyright Katherine Luketina.

(gradually) drained. So, while exact restoration could not be expected, the area would return to a semblance of its former state.

Figure 2.13 Taumatapuhipuhi Geyser in Tokaanu, which has a 2-minute geysering cycle.

At Tokaanu-Waihi-Hipaua there are approximately 60 springs, including several that exhibit eruptive behaviour from time to time and Therefore, can be considered geysers. No doubt there is some influence from the changing level of nearby Lake Taupo, but there is little monitoring of these features so that correlations between lake level and the activities has not been recognised to date.

Other geothermal surface features in the Waikato Region have been submerged beneath the hydro-electric lakes Atiamuri, Whakamaru, Maraetai, and possibly Waipapa.

Approximately two thirds of all natural surface features in the Waikato Region have already suffered substantial modification as the result of human activities. And this begs the question: What proportion of untouched features should remain and be protected in New Zealand, which was once one of the world's great assemblages of natural geothermal activities?

When considering the impact of proposed developments in the Waikato Region the losses it has already sustained should be taken into consideration when weighing the relative importance of the suggested development against the value of the natural features.

The durable sinter formations that remain after the springs that created them ceased flowing at Wairakei, The Spa at Tauhara, and Ohaaki, and that lie submerged beneath the hydro-lake at Orakei Korako, and beneath the hydro-lakes further down the Waikato River, still have cultural, spiritual, scientific, and intrinsic values. Therefore, we introduce the separate definition "recent sinter" to comprise such expanses as are no longer being sustained by further deposition. The date of 1900 is selected to differentiate between recent sinter and ancient sinter because it was only in the 20th century that sinter-depositing geothermal features in the Waikato Region became subject to human intervention on a scale capable of diverting their supply fluid.
(And, although they are called "durable" their small-scale features have readily decayed – see later for further comments on this aspect.)

Not only the "Recent sinters" but also the drowned geysers and other drowned geothermal features at Orakei Korako, and the now empty basins of springs and other features at Wairakei Geyser Valley, the Waiora Valley and the Spa Thermal area, together with the currently inactive features at Whakarewarewa area need to be taken into consideration so that the proportion of the individual geothermal feature types that have already been effectively lost are available for consideration when it comes to applying the results of this analysis to issues of protection and preservation.

See Tables 2 – 4 and 5a – 5c of "Statistics and Analysis of Geothermal Features in the Waikato Region" by Leonie Pipe (2006) which supports this document. Pipe's comprehensive report, in addition to commenting on systems in the Waikato Region, includes statistics from the Bay of Plenty Region for the only other major New Zealand alkaline-chloride dominated areas which were or are located at pre-eruption Rotomahana and Whakarewarewa (in the Rotorua geothermal system).

2.5 Geothermal habitats

Unlike the definitions for other geothermal features, the definition of *Significant Geothermal Terrestrial Habitat* we have chosen (see above) is not based purely on physical properties, but also on biological attributes that arise in part from the history of the particular area. These include the uses to which the particular geothermal system's environs have been put in the past. Thus, there might be influences of weed invasions, animal pests, and land management, including the effects of the use of agricultural chemicals. The areas that have been modified least by such influences are regarded as having higher habitat value in that they represent best the natural state of the habitat. Such near pristine examples are Therefore, accorded a higher "intrinsic" value than those more changed.

We are not able to determine the significant areas of geothermal habitat based on hydrodynamic criteria because other environmental factors determine the quality and rarity of vegetation and fauna habitat present in a geothermal area. However, we can define Significant Geothermal Terrestrial Habitats according to the plant and animal communities that live in them. This has been done in a formal way for terrestrial geothermal habitats in the Waikato Region (Wildland Consultants Ltd, 2004) and in conformity with Appendix 3 of the Waikato Regional Policy Statement (Waikato Regional Council 2002b), which describes any geothermal habitat as meeting the requirement of “Significant Indigenous Vegetation and Significant Habitat of Indigenous Fauna” by virtue of it being nationally uncommon. Waikato Regional Council Technical Report TR2002/15 (Waikato Regional Council 2002a)

A similar assessment has not been made for aquatic habitats, although some of the ecological characteristics of some of these have been described (Duggan & Boothroyd, 2001; Duggan & Boothroyd, 2002; Parkyn & Boothroyd, 2000, Stevens *et al.*, 2003). In any event geothermal aquatic habitats will in all cases fall under the category of “Geothermal wetland, lake, pool, or stream”, so the need to identify them separately is less urgent than that for the terrestrial habitats.

The area of the Waikato Region is approximately 25,000 km^2 (Waikato Regional Council, 1998). The total area of surveyed geothermal terrestrial habitat in the Waikato Region is minute compared to the region’s total land area and consists of 36 isolated small pockets of land and water, covering no more than 580 hectares (5.8 km^2) (Wildland Consultants Ltd, 2004) or approximately 0.0232% of the region’s area. In addition, there are ten known areas of geothermal terrestrial habitat of less than one hectare each that have not been surveyed (Wildland Consultants Ltd, 2004), and there are likely to be some undiscovered or unrecognised areas.

In general, a geothermal vegetation feature does not comprise a single discrete patch of continuous vegetation. Most such features include several separate patches of geothermal vegetation within a closely defined area. The area and number of Significant Geothermal Terrestrial Habitats can reduce as use of the geothermal resource and land surrounding the vegetation adversely affects the habitats, unless protection and rehabilitation of the features is able to keep pace or exceed the rate of destruction and degradation.

Figure 2.14 Geothermal habitat around Te Manaroa Pool in Waikite, with *Hypolepis dicksonioides*. Copyright Shaun Barnett.

Twenty of the Significant Geothermal Terrestrial Habitat features are influenced by both warm ground and geothermal water. Thirteen are influenced only by hot ground. Three others are influenced only by geothermal water, but support particular geothermal terrestrial vegetation types that depend on warm air rising from the geothermal water and affecting vegetation growing on cold ground. These different categories are listed in Table 2.1 below.

Table 2.1 Origins of Geothermal Influence of Significant Terrestrial Habitat

Geothermal System	Mixed origin	Hot ground only	Water-influenced only
Atiamuri	Whangapoa Springs		
Horohoro	Horohoro		
Mokai	Paerata Rd Waipapa Stream		
Ngatamariki	Ngatamariki		
Ohaaki		Ohaaki East Ohaaki West	
Orakei Korako	Red Hills Te Kapua		
Reporoa	Longview Rd Wharepapa		
Rotokawa	Lake Rotokawa	North-east Rotokawa	
Te Kopia	Te Kopia		
Tokaanu-Waihi-Hipaua	Tokaanu	Hipaua	
Waikite	Waikite		
Waiotapu	Maungakakaramea	Maungaongaonga	
	Ngapouri Waiotapu North Waiotapu		
Wairakei-Tauhara	Broadlands Rd Te Kiriohinekai Upper Wairakei Stream	Craters of the Moon Crown Park Crown Rd Karapiti Forest Spa Thermal Park Te Rautehuia Te Rautehuia Stream Waipouwerawera	Hall of Fame Stream Otumuheke Waipahihi

3 Rarity and vulnerability

The Waikato Regional Policy Statement Proposed Change No. 1: Geothermal Section as Amended by Decisions, contains in the first paragraph of page 14 the following text:

> Geothermal surface features are valued for many reasons, but many are highly vulnerable to geothermal system development or to other uses of land and water. Already most of the region's geothermal surface features have been lost or degraded. Maintenance of the variety in characteristics of the regional geothermal resource requires identification of the significant characteristics. For each of these characteristics of the regional geothermal resource, consideration of the frequency of occurrence, the ability to recover from impacts, and the capacity to adapt to a changing situation need to be identified.

As will be seen in the following subsections we provide a particular numerical representation scheme for each of the qualities of rarity, vulnerability to natural influences, and vulnerability to induced changes, as applied to each geothermal feature type, and then we describe how these numbers should be combined in order to assess an "endangerment index" for each type. This then can be used in defining the degree of protection that such a feature type deserves in order to ensure that the Waikato Region retains a full range of the different types, and sufficient examples of each type.[6]

3.1 Rarity

A count of the number of occurrences of a particular type of geothermal feature is, in some cases, too naïve a way to assess its rarity. This is because some features are of easily recognisable and limited physical size while others are of indefinite size. We shall call the former intensive entities and the latter extensive entities. The class of extensive geothermal feature types comprises:

- geothermally heated ground or steaming ground;
- geothermally altered ground;
- recent sinter;
- ancient sinter;
- significant Geothermal Terrestrial Habitat;
- geothermal wetland, lake, pool, or stream.

All the rest are intensive geothermal features.

The problem with counting occurrences of extensive features is exemplified by the following contrived case. Suppose a geothermal habitat covered 1 hectare. Suppose some ecological disaster befell it and what remained was five separated remnants, each 0.1 hectares in area. A simple count would give 5 occurrences after the disaster compared with 1 occurrence beforehand, but the total area of the habitat has halved. Clearly it is the change in area that gives a truer picture of the effect of the event. Thus, it is the total area of that type of geothermal feature that must be used to assess its rarity. There is no such problem with intensive geothermal features for which a straightforward count would reveal their rarity, and we commence with a consideration of these types.

(In fact, Waikato Regional Council takes the more holistic approach and defines a terrestrial geothermal habitat to include all occurrences of such habitat within a confined area that is

[6] Indeed, for features of which there are only very few examples we should be alert to any potential formation of a new example to be able to ensure that it immediately receives what protection is possible to prevent its destruction by human agency.

separated from other geothermal habitat areas by a relatively large area of cold ground. Thus, within a geothermal habitat site there may occur individual pockets of geothermal habitat that are in close proximity to, but not necessarily contiguous with, each other.)

"Rarity" is a qualitative term naming the notion of something that should be high when there are few examples of the particular entity being considered, and low when there are very many examples to be found. But because the number of occurrences of the entity is indeed a number, it should be possible to allocate a related number to "rarity" itself and thereby give it a quantitative meaning.

We now argue for a particular form of relationship for conversion from the number of occurrences, n, to this number, rarity, r, which we suggest accords well with one's instincts as to it's representing the original qualitative meaning of the word.

We start by considering commonness, a sort of opposite of rarity. If there are two entities A, B, (e.g. different types of geothermal feature) being considered, and there is one example of A and two examples of B present, then clearly B is more common than A. However, if there are 20 examples of A and 21 examples of B present, one feels that the commonness of B is only marginally greater than that of A. So, it is not the n values themselves that accord with our instincts for what the relative commonness should be, but rather the ratio of the n values. Thus, we need a logarithmic scale for the commonness. We could use any convenient base for the logarithms, such as 2, or the exponential number e (=2.7182…), and we choose e. Thus, the commonness, c, of an entity will be defined as:

$$c = k \ln n$$

where k is some convenient constant.

Returning to rarity, one's instincts are that this is a sort of complement of commonness – high rarity corresponding to low commonness and low rarity to high commonness. This leads us to assume that:

$$r + c = l$$

where l is a constant.
The numbers k and l are at our disposal, and a convenient (but arbitrary) choice was made to put l = 50 and k = 6. This gives what we regard as a reasonable range of values for r in our present application. For very large values of n, r as given by these formulae has the undesirable property of becoming negative, but the value of n for which this occurs is around 4,000, which is greater than any numbers that actually need to be considered in this application, and the undesirable property is Thus, irrelevant in our context. We display the relationship in graphical form below.

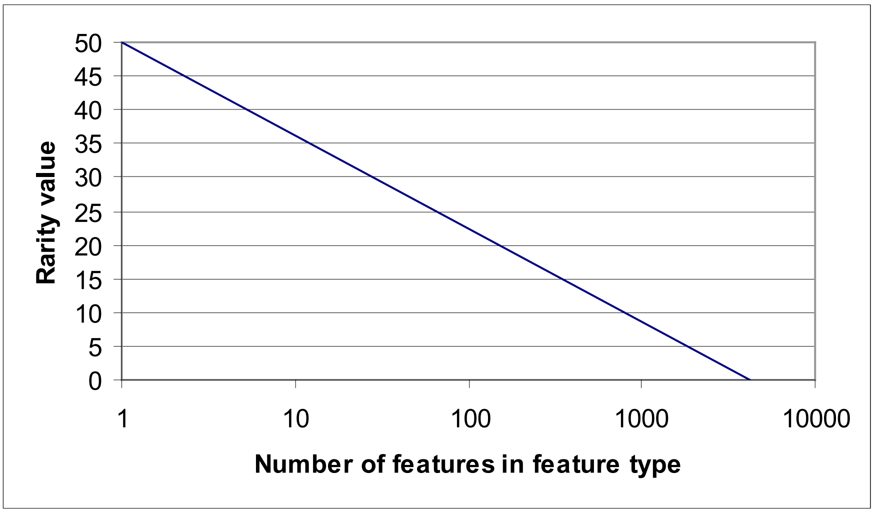


Figure 3.1: Graph of regional rarity values for geothermal feature types

For extensive type geothermal features, we noted above that total areas can be used in place of entity counts and a table of rarities could be prepared. But how to intercalate the rarity scales for the extensive and the intensive geothermal feature types is at this point indeterminate - the process involves a choice. On the grounds of keeping the physical dimensions consistent (and thereby avoiding problems if units were changed) the most defensible approach would seem to be to allocate some sort of unit area to an intensive feature. We suggest 10,000 m^2 to be a suitable unit area.

Waikato Regional Council has compiled a listing of sinter-depositing springs, geysers, mud geysers, and recent sinters within the Waikato Region (Cody *et al.*, 2021). Assessment of the number of occurrences or areas of these and other types of geothermal feature in the region has been performed specifically for this current study and are presented as tables at the conclusion of the report "Statistics and Analysis of Geothermal Features in the Waikato Region" by L. Pipe.

Geothermal springs and seeps require discharge temperatures between 30 °C and 100 °C and are the most common of all feature types, (and occur in almost all countries in the world). Fumaroles, geysers, mud geysers, and most silica-sinter depositing springs, mud pools and hot ground require boiling temperatures, and are less common. The most distinctive geothermally-supported terrestrial ecosystems are generally associated with the hotter features but have not been recognised as being associated with all such features. Therefore, there are fewer such high-temperature ecosystems than there are features such as geysers that might be capable of supporting them.

Almost all geysers deposit sinter and therefore comprise essentially a sub-set of Spring vigorously depositing sinters. Exceptions (See non-sinter-depositing geyser in the list of definitions) are two intermittently erupting features at Ketetahi (Cody *et al.*, 2021) and a few at White Island (Cody *et al.*, 2002) that do not deposit sinter. Geysers occur in regions that also have sinter-depositing springs, although there are many locations with sinter-depositing springs but no geysers. Worldwide there are estimated to be 1070 geysers in 52 localities in 20 countries (Bryan, 1995). A recent count showed that New Zealand at present contains approximately 79 geysers: 49 in the Waikato Region (Cody *et al.*, 2021) and approximately 30 at Rotorua and Waimangu in the Bay of Plenty Region (Cody *et al.*, 2002; Lloyd, 1975). Only approximately one in four sinter-depositing springs in the Waikato Region is a geyser (Cody *et al.*, 2021).

Mud geysers are very rare. They are mud pools with particular thermodynamic and hydro-dynamic eruptive characteristics that set them apart. Five mud geysers are known to have been active in the Waikato Region (Cody *et al.*, 2021), namely one each at Wairakei, Orakei Korako, Te Kopia, Waiotapu, and Mokai. However, the Wairakei mud geyser is now extinct. It was one of the ill-fated set of features known as variously as the Alum Lakes and Waiora Lakes, which started draining in 1997 and are now largely emptied following fracturing of the aquiclude below them due to subsidence induced by large-scale geothermal extraction (Bromley, 2001).

Also, in the Bay of Plenty Region, there is one at Tikitere and another (which also counts as a crypto-geyser) at Waimangu. Just one in the U.S.A. is known to us. This is at Pocket Basin in Yellowstone National Park (T.Scott Bryan and D Goldberg, pers. comm, 2002), although we suspect others probably exist there.

The rarest active geothermal features are molten-sulphur producing springs. Only two are known in New Zealand - one in Te Whangi o te Rangi (also known as "Blue Lake" and as "Echo Lake") which occupies an elongated hydrothermal explosion crater at Waiotapu, and one in another hydrothermal explosion crater on the same geological fracture and just downstream of Bridal Veil Falls in the Waiotapu Scenic Reserve. In recent times molten sulphur globules have come up rarely, but there was a significant production from both features in 1954 following seismic activity. (Lloyd 1959). Evidence of earlier persistent production from Te Whangi o te Rangi is to be found in cone-shaped mounds of stranded silica mud pisolites[7] bordering the stream that drains the lake westwards into the Waiotapu Scenic Reserve. These pisolites contain concentrations of elemental yellow sulphur, which evidently represents the reverted allotropic form of what had originally been molten black sulphur.

Table 3.1 below lists the most recently available figures as determined by Pipe (2006) for geothermal feature types in order of decreasing rarity, with brief comments regarding the reliability of their counts. Features that are counted in a subset of other feature types are included in the count of the superset.

[7] Hard inorganic depositions resembling a pea in size and shape

Table 3.1: Regional rarity of geothermal features

(* denotes an extensive class feature)

Feature Type	Subset of:	Reg-ional Rarity	No. in region	Comments
Molten sulphur-producing spring	Geothermal spring or seep	46	2	Just 2 occurrences are known in the Waikato Region, *viz.* a spring within Te Whangi o te Rangi and another within a hydrothermal explosion crater just downstream of Bridal Veil Falls, both in the Waiotapu Scenic Reserve.
Mud geyser	Mud pool	42	4	There are 4 known in the Waikato Region, one each at Te Kopia, Mokai, Orakei Korako, and Waiotapu.
Superheated Fumarole	Fumarole	34	15 ± 5	A small proportion of fumaroles emit gases at temperatures greater than 100°C.
Geothermal wetland, lake, or stream		28	40 – 45	Forty geothermal wetlands, lakes, and streams in the Waikato Region have been listed (Stevens *et al.*, 2003). We suspect that there may a few more as yet unrecognised sites.
Geyser	Most (but not all) geysers are Spring vigorously depositing sinters)	27	49 ± 5	Cody *et al.* count 49 known in the Waikato Region that have not been drowned by the creation of the hydroelectric Lake Ohakuri (Cody *et al.*,2021.). Pipe (2006) counts 28. Cody's *et al.*'s higher count may be due to Cody's careful observation of many small features on Artist's Palette at Orakei Korako that occasionally have periods of frequent eruption followed by periods of quiescence. Cody *et al.* also count 4 geysers at Waiotapu, 4 at Tokaanu, and 2 acid geysers at Ketetahi that are omitted from Pipe's count. While those drowned are not extinct in that they would likely recover if the water level were lowered, they are not counted here because they currently do not erupt. However, these are included in the Spring vigorously depositing sinters category. Geysers can be ephemeral and some of those that are currently considered dormant may in fact be extinct. Conversely, there may be some geysers as yet undiscovered, or springs not recognised as geysers because their eruptions have not been observed. Because of the natural variability of geysers, and the possibility that there are some unrecognised geysers, we estimate the range to be up to 5 geysers either side of the counted number.
Hydrothermal eruption crater		24	80 ± 10	Many areas of geothermally altered ground and heated or steaming ground have more than one eruption crater. Hydrothermal eruptions are a relatively rare phenomenon, but they leave behind enduring and substantial landscape features.
Fumarole		19	170 ± 20	
Geothermal collapse pit		18	200 ± 20	Since geothermal collapse pits are formed by continuous processes rather than the rarer hydrothermal eruption processes, the number and distribution of geothermal collapse pits is estimated to be greater than that of eruption craters.

Feature Type	Subset of:	Reg-ional Rarity	No. in region	Comments
Recent sinter		18	205 ± 10 * (0.21 km^2)	There are 205 sinter-depositing springs known in the Waikato Region that have ceased to flow in recent years, leaving sinter terraces and cones as remnant features (Cody *et al.*, in prep.). There may have been an error of up to ten springs in the documenting of them.
Mud pool		16	270 ± 20	Many areas of heated or steaming ground have more than one mud pool, although some do not have any. According to Lloyd (1972), there are 99 mud pools that remain above water level at Orakei Korako alone.
Unsubmerged spring vigorously depositing sinter	Spring vigorously depositing sinter	14	410 ± 20	The range estimate covers counting errors, the fact that springs come and go, and the possibility that there are some undiscovered springs. In particular, we do not know how many such springs are to be found in the Horomatangi Geothermal System on the bed of Lake Taupo.
Significant Geothermal Terrestrial Habitat	Geothermally heated or steaming ground	12	40 – 50* (579 ha)	There are 35 known significant geothermal vegetation sites in the Waikato Region covering a total area of 579 ha (Wildland Consultants Ltd, 2004). A further 10 small geothermal vegetation sites in the Waikato Region have been described but not ranked (Given, 1996). There may be other sites that have not been described by Given. Not all of the sites unranked by Given or undescribed by him will be Significant. Overall, we estimate that there may be up to 10 known or unknown sites that could be Significant.
Geothermally heated or steaming ground		11	44 – 49* (7 km^2)	There are at 44 known sites in the Waikato Region (Given, 1996). We suspect that there may be a few more as yet unrecognised sites. The area of this category will be greater than that for Significant Geothermal Terrestrial Habitat, because it also includes those areas too hot for vegetation and those that are elevated in temperature relative to surrounding land, but still cool enough for non-geothermal vegetation to colonise.
Spring vigorously depositing sinter	Geothermal springs or seeps	10	810 ± 30	This number includes those drowned by the raising of water levels in Lake Taupo and the Waikato River system.
Geothermal spring or seep		8	1480 ± 100	The number given here is the total existing unsubmerged discharging features whether sinter-depositing or not. (cf Pipe, 2006.)
Geothermally altered ground		7	150 ± 50 * (>12 km^2)	Several geothermal collapse pits may occur on an area of geothermally altered ground, so altered ground is estimated to be rarer than collapse pits. This remnant feature is estimated to be three times as common as areas of ground that are currently hot.
Ancient sinter		?	large *	The Coromandel peninsula and other areas in the Waikato Region contain many instances of ancient sinter. Because it is the most durable of remnant geothermal expressions, we estimate that it is the most common. However, as much of it is buried, we have no way of knowing how many occurrences there are.

3.2 Vulnerability *versus* resilience and viability

When deciding on priorities for conservation of biological systems (populations or ecosystems), one accepted method is to analyse and rank the candidate systems' rarity, resilience, and viability (Molloy and Davis, 1994). In this context resilience is a measure of the ability to withstand events such as storms and changes to limiting factors such as climate, food supply, infection, and introduction of predators. Viability is a measure of the system's ability to continue indefinitely given the existing and likely future range of conditions. Viability relates to such questions as: Is there sufficient food available to the population in the long term, is there a sufficiently large breeding population to maintain numbers, are the conditions right for breeding, is the gene pool large enough to ensure adaptability?

We attempted to adapt this method of analysis to geothermal features. In this context, both resilience and viability are related to a geothermal feature's vulnerability to changes in its host system's environmental state. The usual use for rarity, resilience, and viability parameters is in determining which threatened ecosystem among several is most likely to respond to an input of a finite sum of conservation money and effort. However, the task at hand is somewhat different in that its purpose is to assist Waikato Regional Council in developing policy about maintaining the extent and variety of geothermal features in the Waikato Region.

Therefore, it was found necessary to modify the method to address the parameters of rarity, vulnerability to natural changes in the environment, and vulnerability to artificial changes.

We shall later address changes induced by human agency and first concentrate on natural changes including effects caused by meteorological influences.

3.3 Vulnerability to natural variations and changes

Some types of geothermal feature require that certain of their host system parameter values remain locally within relatively restricted bounds in order to behave in their characteristic manner. Viability then relates to the probability that hydrothermal system parameter values lie within those bounds, while resilience is a description of whether or not, and to what degree, a feature temporarily subjected to some significant departure of parameter values beyond those bounds is able to recover and resume its normal behaviour.

It should be emphasised that non-biological type geothermal features and biological type geothermal features have qualitatively different responses to parameter value excursions. If, after such an event, system parameter values and meteorological effects locally permit a geyser to play, then it will play, but if the excursion caused the biological geothermal feature's living organisms to die, the return of the physical conditions to congenial values will alone certainly not cause such a feature to recover. There might be recovery after some time, due to recolonisation and re-establishment of the ecosystem, but this would depend on sources of the lost organisms being at hand.

The (natural) viability of a geothermal feature is a measure of variability of the host system. If the hot geothermal system is fairly stable a dependent feature may remain active because locally the range of system and meteorological parameter values does not stray beyond the bounds for its survival, whereas if the system is quite variable geothermal feature viability will be reduced.

For purely geophysical aspects of a geothermal feature, it might at first seem that if, after an excursion, parameter values returned to those that prevailed before the excursion the activities would return precisely to what they had been beforehand. So, for instance, eruptions of a geyser would return to their original range of heights, intervals, discharge quantities etc. But to some extent this depends upon the length of time the excursion lasted. If that time were of the order of a few years the geometry or integrity of the structure might well have altered as a result of sinter deposition within the fluid conduits, or decay of sinter as a result of weathering. Also, given the dynamic state of intense systems that support geysers, the chances of precise restoration of parameter values for the whole set of hydrodynamically strongly-connected features is in practice unlikely. So the effects of human agency can well be masked to some extent by these natural changes.

Geysers require, as a fundamental cause of their existence that the hydrothermal system hosting them be high-temperature. But it is the very two-phase nature of such a system that causes variability and unpredictability in the host system. Two-phase geothermal systems are often very dynamic with variable outflows of heat and fluids, especially on local distance scales of a few tens of metres. Thus, geysers are inevitably subject to conditions that could limit their viability and on varying time scales they could become active or subside into inactivity.

In this sub-section we note that we are considering a geothermal feature as comprising not only the physical discharge and its discharge structure but also any dependent structures and any dependent ecosystem that might exist within the “area” of that feature according to its definition in the list of feature types presented in sub-section 2.2.

The question now arises as to whether we can ascribe precise numerical values to the concepts of “resilience” and “viability” in a manner similar to what was done for “rarity”. For purely geophysical features viability relates to the probability that locally hydrothermal system parameter values (and also meteorological parameter values) lie within certain ranges, while for biological type geothermal features it relates also to the probability of re-establishment if partial or complete extinction of its ecological elements occurs as a result of excursions beyond the bounds of those ranges.

If p_i be the probability per unit time that element i locally will be found inside a given range of values, the probability per unit time that all elements will be found within a set of the given ranges of values of those parameters is Product(p_i). The probability per unit time, therefore, that at least one parameter value lies outside its given range is 1-Product(p_i). If the given ranges are those for which the geothermal feature behaves in its characteristic manner, then 1-Product(p_i) is a measure of that feature’s vulnerability.

Unfortunately, the values of the p_i are not known and furthermore can be expected to vary widely from feature to feature even among features of the same class, depending on the local conditions at the feature’s site, and depending on the relative stability of the system itself. Therefore, we are not able to calculate the vulnerabilities of individual features. However, we can estimate qualitatively and consider qualitative arguments concerning the relative vulnerabilities of different types of geothermal feature under what might be called average conditions in a typical geothermal system. We proceed Therefore, to determine a hierarchy of geothermal feature types ordered according to our assessment of their relative average vulnerabilities. This hierarchy is presented in Table 3.2 below, with explanatory comments included. Where necessary further comments about the entries and their ordering are presented after the table.

Table 3.2 below lists the vulnerability to natural influences for each feature type.

Table 3.2: Vulnerability of Geothermal Features to Natural Influences

Feature Type	Constraints	Vuln-erab-ility
Recent sinter	By definition receives no new deposits from geothermal system. Delicate formations rapidly degrade. (~1 – 10 years)	16
Mud geyser	Requires intermittent or continuous discharge of steam through mud pool. Can be regarded as surface manifestation of crypto-	15

Feature Type	Constraints	Vuln-erab-ility
	geyser or fumarolic activity (respectively) within a restricted type of topographic and geometric environment.	
Geyser	Requires discharge of boiling temperature water and steam. Requires the restricted range of geometries involving high permeability flow paths and adequate reservoir that permit alternating styles of discharge behaviours. Therefore, geysers are least viable of all water-fed features.	14
Super-heated fumarole	Requires discharge of high-temperature steam, Vulnerable to fluid diversion and fluid temperature decrease.	13
Fumarole	Requires discharge of steam at the local boiling point. Usually located above water-table. Vulnerable to fluid diversion.	12
Molten sulphur-producing spring	Requires the presence of elemental sulphur in the strata through which the geothermal channels pass, and permanent gases that will, in passing through, be partly trapped in and buoy the molten sulphur sufficiently to bring some to the surface. Thus, there must be something like a fumarole at the detachment site. The geographic/topographic setting is not so restrictive as for a fumarole. Exhaustion of the supply of S would cause spring to revert to just a spring. Similarly a drop in fluid temperature to below the melting point of S would cause the same result.	11
Mud pool	Located in depression and usually above local water table; requires steam and/or gas input and modest rainwater input; can form on steaming ground. Mud volcano development dependent on restrictive and persistent viscosity constraints. Weakly vulnerable to fluid diversion	10
Significant Geothermal Terrestrial Habitat	A geothermal habitat may exist on warm ground or in a geothermal spring discharge area.	9
Geothermally heated or steaming ground	No biological constraints, located above local water table, elevated temperatures required (usually at or close to 100°C) – precursor to geothermally altered ground. Weakly vulnerable to fluid diversion.	8
Unsubmerged spring vigorously depositing sinter	These do not require that the water reaches the surface at boiling temperature, so are less vulnerable than steam-fed features and geysers.	7
Spring vigorously depositing sinter	These do not require that the water reaches the surface at boiling temperature, so are less vulnerable than steam-fed features and geysers.	7
Geothermal wetland, pool, lake or stream	Requires specific geographic setting (topographic low). Dominantly fed by multiple hot spring discharges, together, usually, with meteoric water. Relatively low temperature. Vulnerable to behaviour of sources and meteorology. But can survive failure of some of the inputs	6
Geothermal spring or seep	Requires liquid water supply between 30°C and 100°C. Sinter deposition not essential	5
Geothermal collapse pit	No active geothermal input necessary, distinctive geomorphology, gravitationally unstable. Disappears by wall	4

Feature Type	Constraints	Vuln-erab-ility
	collapse, enlargement and coalescence on estimated time scale ~ $10^2 – 10^4$ years.	
Hydrothermal eruption crater	No active geothermal input required, subject to weathering, distinctive geomorphology, large craters last for sub-geological time scale ~ $10^3 – 10^5$ years	3
Geothermally altered ground	No active geothermal input required, erodes, but has no particular geomorphology.	2
Ancient sinter	No active geothermal input, resistant, degrades by geological influences on geological time scale	1

The least vulnerable types of geothermal features must be those for which the hydrothermal system parameter ranges and meteorological parameter ranges are least restrictive. Those, without doubt, are the more durable of the relict features, whose continued existence is largely independent of the state of the hydrothermal system that created them, and comprise ancient sinter, geothermally altered ground, hydrothermal eruption craters, and geothermal collapse pits.

Ancient sinters survive at the surface or buried in very many localities, for geological time scales, for instance being found in the Tertiary volcanics in the Coromandel region. But sinter structures include delicate forms as well as durable massive deposits. Examples are stalactites and fretwork patterns and cones such as Te Komutumutu (the Brain Pot) at Whakarewarewa in the Bay of Plenty Region, also sinter splash features such as sometimes border flow channels and even turn the channels into tubes. These are very vulnerable if the feeding fluids no longer refresh them and the structures can exhibit pronounced decay over time scales of 1 – 10 years. When one is concerned about these delicate examples, vulnerability is increased to the extent of the vulnerability of the feeding feature, and perhaps even more than that, because the feeding feature could well revive when the hydrothermal system locally returns to a state where it again becomes active, but in the meantime dependent sinter formations might already have decayed or partly decayed. For that reason “recent sinter” is allocated the position of being the *most* vulnerable of geothermal features.

Geothermally altered ground is much softer than sinter so could be eroded relatively easily. But it has no particular morphology so there is no essential loss if it is sculpted by natural processes. If it becomes buried and therefore, protected it too can survive for geological time scales.

3.4 Vulnerability to artificial changes

We now address the effects of disturbances caused by human agency. Each type of feature will be given a ranking based on an aggregate of numbers that represent a qualitative estimate of vulnerability on a five-value scale when it is subjected to two types of interference: interference with the flow of heat and water to the feature, and interference with the feature at the surface. This estimate is applied to the three major aspects of each feature – its hydrodynamic behaviour, structural nature, and its dependent geothermal ecosystem. Thus, there will be six entries for each geothermal system type. The five-value scale for each entry (0, 1, 2, 3, or 4) corresponds to the interference respectively causing: zero effect; slight effect; moderate effect; severe effect; or total destruction. Justification columns are provided, with the first relating to fluid extraction and the second relating to surface interference. Of course, human “interference” can be relatively modest – such as occurs when a geothermal area is developed for the convenience of tourists by the establishment of walking paths, bridges etc, or by channelling geothermal water, already discharged from some feature, to provide a bathing facility, or to provide warmth for glasshouses. Or it can be destructive of the natural behaviour of a geothermal system by massive extraction of geothermal fluids. This has been the case when systems are exploited to generate electricity or provide industrial-scale heating. And sometimes it is the sum total of small extractions, such as has occurred from the Rotorua geothermal system to provide heating and bathing facilities for a moderate-sized city that has presented a cumulative destructive drain on the system. Table 3.4 below lists the vulnerability to induced changes for each feature type.

Table 3.3: Vulnerability of Geothermal Features to Induced Changes

(0 no effect, 1 slight effect, 2 moderate effect, 3 severe effect, 4 total destruction)

Feature Type	Charact-eristic	Ideal	Vulnerability to Fluid Extraction		Vulnerability to Surface Interference		Vulner-ability Sum
			Score	Reason	Score	Reason	
Geyser	Hydro-dynamic	No decrease in height, volume or frequency of eruptions	3-4	Fluid extraction causes cessation of flow in sinter-depositing springs and geysers.	3	Alteration of sinter formations adversely affects natural eruptive behaviour.	20-23
	Structural	No decrease in extent and undisturbed nature of geyserite sinter formations and pool bed	3-4	Once fluid flow ceases, sinter deteriorates.	4	Sinter formations are brittle and easily damaged.	
	Biological	No reduction or adverse alteration of natural geothermal ecosystem	3-4	Once fluid flow ceases, dependent geothermal ecosystem can no longer survive.	4	Once fluid flow ceases or is redirected at surface, dependent natural geothermal ecosystem can no longer survive.	
Unsub-merged spring vigorously depositing sinter, Spring vigorously depositing sinter	Hydro-dynamic	No decrease in flow, heat content, or concentration of minerals in outflow or in mineral deposition rate	3-4	Fluid extraction causes cessation of flow in sinter-depositing springs and geysers.	1	Flow characteristics are largely unaffected by surface interference	17-21
	Structural	No decrease in extent of, or interference with, sinter formations and pool bed	3-4	Once fluid flow ceases, sinter deteriorates.	4	Sinter formations are brittle and easily damaged.	
	Biological	No reduction or adverse alteration of natural geothermal ecosystem	3-4	Once fluid flow ceases, dependent geothermal ecosystems can no longer survive.	3-4	Once surface fluid flow is redirected, dependent natural geothermal ecosystems might no longer survive.	
Significant geo-thermal habitat	Hydro-dynamic	No alteration in fluid flow, heat content, or concentration of geothermal minerals in outflow	2-3	Many habitats depend on steam-fed features so effect of fluid extraction might not be as marked as on sinter springs.	2-3	Flow characteristics may not be affected by surface interference	16-20
	Structural	No decrease in extent and undisturbed nature of geothermally influenced water and land.	2-3	Many habitats depend on steam-fed features so effect of fluid extraction might not be as marked as on sinter springs.	4	Land and surface water drainage reduces extent of features.	

Feature Type	Charact-eristic	Ideal	Vulnerability to Fluid Extraction		Vulnerability to Surface Interference		Vulner-ability Sum
			Score	Reason	Score	Reason	
	Biological	No decrease in extent and undisturbed nature of natural geothermal ecosystems.	2-3	Many habitats depend on steam-fed features so effect of fluid extraction might not be as marked as on sinter springs.	4	Land and surface water drainage reduces extent of ecosystems.	
Geo-thermal wetland, lake, or stream	Hydro-dynamic	Maintenance of natural volume, heat and chemical characteristics of both geothermal and fresh water inputs, no extraction of water or input of contaminants	2	Most geothermal wetlands, lakes and streams contain a mixture of geothermal and fresh water so effect of reduction of geothermal input is less than for features with entirely geothermal input.	2-3	Reduction of fresh water inputs, and land and surface water drainage reduces extent of features.	13-16
	Structural	No damming or disturbance to bed and banks	1-2	Bed and banks are barely affected by alteration to flow regime.	3	Bed and banks are strongly affected by surface alteration.	
	Biological	No decrease in extent and undisturbed nature of natural geothermal ecosystems	2	Most geothermal wetlands, lakes and streams contain a mixture of geothermal and fresh water so effect of fluid extraction and Therefore, geothermal ecosystems similar to that on geothermal springs and seeps.	3-4	Land and surface water drainage reduces extent of ecosystems.	
Mud Geyser	Hydro-dynamic	No decrease in height, volume or frequency of eruptions	3	Behaviour of some steam-fed features is less vulnerable to fluid extraction than that of sinter springs.	2-3	Land and surface water drainage alters volume of fresh water in pool.	15-17
	Structural	No decrease in extent and undisturbed nature of solid mud formations, land surface and pool bed	3	Extent of steam-fed features is less vulnerable to fluid extraction than that of sinter springs.	3-4	Mud formations are vulnerable to surface interference.	
	Biological	no reduction or adverse alteration of natural geothermal ecosystem	2	Ecosystems in hot mud are limited, and geothermal input is not particularly vulnerable to fluid extraction.	2	Ecosystems in hot mud are limited but can be upset by surface interference.	

Feature Type	Charact-eristic	Ideal	Vulnerability to Fluid Extraction		Vulnerability to Surface Interference		Vulner-ability Sum
			Score	Reason	Score	Reason	
Super-heated Fumarole	Hydro-dynamic	No decrease in upflow of heat and steam	2	Fluid extraction may increase upflow of heat and steam.	2	Surface interference can have a limited effect on upflow of heat and steam.	13-16
	Structural	No decrease in extent and undisturbed nature of vent and any associated mineral deposits	1-2	Fluid extraction has limited effect on vent geometry.	3-4	Vents can be filled in and deposits removed.	
	Biological	No decrease in extent and undisturbed nature of natural geothermal ecosystems	2	Fluid extraction may increase upflow of heat and steam and has limited effect on vent geometry, so ecosystems are not very vulnerable to fluid extraction.	3-4	Vents can be filled in and deposits removed, destroying ecosystems.	
Fumarole	Hydro-dynamic	No decrease in upflow of heat and steam	2	Fluid extraction may increase upflow of heat and steam.	2	Surface interference can have limited effect on upflow of heat and steam.	14-16
	Structural	No decrease in extent and undisturbed nature of vent and any associated mineral deposits	2	Fluid extraction has limited effect on vent geometry.	3-4	Vents can be filled in and deposits removed.	
	Biological	No decrease in extent and undisturbed nature of natural geothermal ecosystems	2	Fluid extraction may increase upflow of heat and steam and has limited effect on vent geometry, so ecosystems are not very vulnerable to fluid extraction.	3-4	Vents can be filled in and deposits removed, destroying ecosystems.	
Geo-thermally heated or steaming ground	Hydro-dynamic	No decrease in upflow of heat and steam	1-2	Fluid extraction may increase upflow of heat and steam.	1-2	Surface interference can have limited effect on upflow of heat and steam.	10-15
	Structural	No decrease in extent and undisturbed nature of land surface	1-2	Fluid extraction may increase area of heated ground.	2-3	Area can be levelled, excavated, covered, or trampled.	
	Biological	No decrease in extent and undisturbed nature of natural geothermal ecosystems	2	Fluid extraction may increase upflow of heat and steam, so ecosystems are not very vulnerable to fluid extraction.	3-4	Vents can be filled in and deposits removed, destroying ecosystems.	

Feature Type	Charact-eristic	Ideal	Vulnerability to Fluid Extraction		Vulnerability to Surface Interference		Vulner-ability Sum
			Score	Reason	Score	Reason	
Mud pool	Hydro-dynamic	No decrease in upflow of heat and steam	2	Fluid extraction may increase upflow of heat and steam.	2	Land and surface water drainage alters volume of fresh water in pool, but this is not as critical as for mud geyser.	12-13
	Structural	No decrease in extent and undisturbed nature of land surface, solid mud formations, and pool bed	2	Fluid extraction may increase upflow of heat and steam and area of mud pool.	3	Mud formations are vulnerable to surface interference, but not as vulnerable as the large formations of some mud geysers.	
	Biological	No decrease in extent and undisturbed nature of natural geothermal ecosystems	1-2	Ecosystems in hot mud are limited, and geothermal input is not particularly vulnerable to fluid extraction.	2	Ecosystems in hot mud are limited but can be upset by surface interference.	
Molten sulphur-producing spring	Hydro-dynamic	No change in discharge of molten sulphur and other geothermal fluids	1-3	Fluid extraction could disrupt high temperature supply	1	Superficial alteration would not affect supply mechanism much	12-16
	Structural	No change in extent and nature of vent and any associated mineral deposits	2	Fluid extraction has limited effect on vent geometry	3-4	Vents can be filled in and deposits removed	
	Biological	No change in extent and nature of natural geothermal ecosystems	2	Fluid extraction could either increase or decrease temperatures	3-4	Vents can be filled in and deposits removed, destroying ecosystems	
Geo-thermal spring or seep	Hydro-dynamic	Maintenance of natural volume, heat and chemical characteristics of water	2-3	Most springs produce water of meteoric or mixed origin, so effect of fluid extraction is not as marked as on sinter springs.	1	Flow characteristics are largely unaffected by surface interference	11-15
	Structural	No decrease in extent and undisturbed nature of land surface and pool bed	1-2	Most springs do not deposit sinter, so pool surface and surrounds are more resilient than sinter deposits.	3-4	Land and surface water drainage reduces extent of features.	
	Biological	No decrease in extent and undisturbed nature of natural geothermal ecosystems	2	Most springs produce water of meteoric or mixed origin so effect of fluid extraction and therefore, geothermal ecosystems is not as marked as on sinter springs.	2-3	Land and surface water drainage reduces extent of ecosystems.	

Feature Type	Charact-eristic	Ideal	Vulnerability to Fluid Extraction		Vulnerability to Surface Interference		Vulner-ability Sum
			Score	Reason	Score	Reason	
Hydro-thermal eruption crater	Hydro-dynamic	No decrease in fluid flow, heat content, or concentration of geothermal minerals in outflow	0	Geothermal input not essential, so there can be no effect from fluid extraction.	0	Geothermal input not essential, so there can be no effect on fluid flow from surface interference.	7
	Structur al	No artificial alteration to crater floor, crater sides, and surrounding breccias, and no artificial removal of material from or input of material to the crater	0	Geothermal input not essential, so there can be no effect from fluid extraction.	4	Feature cannot regenerate and is composed of unstable altered ground so is vulnerable to surface interference.	
	Biologic al	No invasion of crater sides, surrounds, or floor by exotic species	0	Geothermal input not essential, so there can be no effect from fluid extraction.	3	Lack of geothermal input renders feature vulnerable to invasion by exotic species.	
Geo-thermally altered ground	Hydro-dynamic	No decrease in fluid flow, heat content, or concentration of geothermal minerals in outflow	0	There is no critical geothermal input remaining, so there can be no effect from fluid extraction.	0	There is no critical geothermal input remaining, so there can be no effect on fluid flow from surface interference.	6-7
	Structur al	No disturbance to land formations or covering of land formations with other matter	0	There is no critical geothermal input remaining, so there can be no effect from fluid extraction.	3-4	Feature cannot regenerate and is composed of unstable altered ground so is vulnerable to surface interference.	
	Biologic al	No invasion of ground by exotic species	0	There is no critical geothermal input remaining, so there can be no effect from fluid extraction.	3	Lack of geothermal input renders feature vulnerable to invasion by exotic species.	
Geo-thermal collapse pit	Hydro-dynamic	No decrease in fluid flow, heat content, or concentration of geothermal minerals in outflow	0	There is no critical geothermal input remaining, so there can be no effect from fluid extraction.	0	There is no critical geothermal input remaining, so there can be no effect on fluid flow from surface interference.	7-8
	Structur al	No artificial alteration to crater floor, crater sides, and surrounding breccias, and no artificial removal of material from or input of material to the crater	0	There is no critical geothermal input remaining, so there can be no effect from fluid extraction.	4	Feature cannot regenerate and is composed of unstable altered ground so is vulnerable to surface interference.	

Feature Type	Charact-eristic	Ideal	Vulnerability to Fluid Extraction		Vulnerability to Surface Interference		Vulner-ability Sum
			Score	Reason	Score	Reason	
	Biological	No invasion of crater sides, surrounds, or floor by exotic species	0	There is no critical geothermal input remaining, so there can be no effect from fluid extraction.	3-4	Lack of geothermal input renders feature vulnerable to invasion by exotic species.	
Recent sinter	Hydro-dynamic	No decrease in heat, fluid, and mineral flow	4	Fluid extraction prevents regeneration.	0	There is no critical geothermal input remaining, so there can be no effect on fluid flow from surface interference.	16-19
	Structural	No decrease in extent and undisturbed nature of sinter formations and no covering of sinter formations with other matter	4	Fluid extraction prevents regeneration.	3-4	Feature is composed of unstable altered ground and is vulnerable to surface interference.	
	Biological	No invasion of sinter by exotic species	3-4	Fluid extraction prevents regeneration and permits invasion.	2-3	Lack of geothermal input renders feature vulnerable to invasion by exotic species, but sinter is harder to colonise than altered ground.	
Ancient sinter	Hydro-dynamic	No decrease in heat, fluid, and mineral flow	0	There is no geothermal input necessary, so there can be no effect from fluid extraction.	0-1	There is no geothermal input necessary so there is little effect from surface interference.	3-6
	Structural	No decrease in extent and undisturbed nature of sinter formations and no covering of sinter formations with other matter	0	There is no geothermal input necessary, so there can be no effect from fluid extraction.	2-4	Feature cannot regenerate and is composed of unstable altered ground so is vulnerable to surface interference.	
	Biological	No invasion of sinter by exotic species	0	There is no critical geothermal input remaining, so there can be no effect from fluid extraction.	1-2	Lack of geothermal input renders feature vulnerable to invasion by exotic species, but sinter is harder to colonise than altered ground, and weathered nature of ancient sinter means colonisation will not substantially affect the sinter.	

4 Recommendations

4.1 Definition of significant geothermal features

All geothermal features and geothermal areas are rare in terms of the proportion of land that is covered by them. Some types of features and areas are rarer than others. In order to protect the variety of geothermal features, greater rarity requires greater protection.

All discharging geothermal features are vulnerable to natural influences such as weathering and changes in the hydrodynamics of the parent geothermal system.
The rarest geothermal features are those that require the most restricted conditions for their existence and those conditions are easily upset by external changes such as the extraction of fluid for electricity generation. Thus, there is some correlation between rarity and vulnerability, but it is not a direct coupling.

The entries for rarity and vulnerability for each geothermal feature type, combine to provide an aggregate which determines the overall rarity and vulnerability, which in turn determines those feature types needing greater protection in order to maintain to some degree the extent and variety of geothermal features in the Waikato Region. These feature types are accordingly described as Significant Geothermal Features.

The table below shows the overall rarity and vulnerability aggregates for each feature type with the aggregate score being the total of the highest values of all the rarity and vulnerability scores:

Table 4.1: Rarity and Vulnerability Aggregates

Feature Type	Regional Rarity	Vulnerability to:			Aggregate Score
		Natural influences	Extractive uses	Surface activities	
Molten sulphur-producing spring	46	11	5-7	7-9	71
Mud geyser	42	15	8	7-9	71
Superheated Fumarole	34	13	5-6	8-10	64
Geyser	27	14	9-12	11	64
Recent sinter	18	16	11-12	5-7	51
Geothermal wetland, lake, or stream	28	6	5-6	8-10	47
Fumarole	19	12	6	8-10	47
Significant Geothermal Terrestrial Habitat	12	9	6-9	10-11	41
Spring vigorously depositing sinter	10	7	9-12	8-9	39
Unsubmerged spring vigorously depositing sinter	14	7	9-12	8-9	39
Mud pool	16	10	5-6	7	38
Geothermally heated or steaming ground	11	8	4-6	6-9	34
Hydrothermal eruption crater	24	3	0	7	33
Geothermal collapse pit	18	4	0	7-8	29
Geothermal spring or seep	8	5	5-7	6-8	24
Geothermally altered ground	7	2	0	6-7	16
Ancient sinter	?	1	0	3-7	–

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