Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

Definition and Listing of Significant Geothermal Feature Types in the Waikato Region

Ronald F. Keam[2], Katherine M. Luketina[1], and Leonie Z. Pipe[2]

[1]Waikato Regional Council, PO Box 4010, Hamilton, New Zealand

katherine.luketina@ew.govt.nz

[2]Physics Dept, University of Auckland, Private Bag 92019, Auckland, New Zealand

r.keam@auckland.ac.nz

Keywords: protection of geothermal features, New Zealand, Waikato Region, environmental aspects

ABSTRACT

The Waikato Regional Council is developing policies for assessing a suitable balance between use and environmental protection of geothermal resources within its regional boundaries. One of these developments involves attempting to determine a rational approach for establishing criteria for protection by defining Significant Geothermal Features and the present paper outlines progress to date with this endeavour. We define geothermal feature types, and then attempt to assess the degree to which they require special efforts at protection based on considerations of rarity and vulnerability. We identify clearly the types of feature according to the geothermal processes that create and sustain them. We also define the "area" of each type of feature in order to provide certainty as to what we regard as being its surface boundary.

We suggest a particular numerical representation scheme for each of the factors "rarity", "vulnerability to natural changes" and "vulnerability to artificial changes" as applied to each geothermal feature type, and then in due course we shall argue for a way in which these numbers should be combined in order to assess an "endangerment index" for each type. This is then available for possible use in defining the degree of protection that such a feature type deserves in order to ensure that New Zealand retains a full range of the different types, and sufficient examples of each type.

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 call the first intensive entities and the latter extensive entities. We suggest a method for putting these two entities on an equivalent footing.

When considering vulnerability, we first concentrate on effects caused by natural changes including meteorological influences and then address responses to changes induced by human agency.

1. INTRODUCTION

New Zealand's environmental legislation devolves the management of environmental matters to sub-national units of local government known as regional councils, and requires them to promote the sustainable management of natural and physical resources for current generations and the reasonably foreseeable needs of future generations. Accordingly, since 1991 the Waikato Regional Council has been developing, implementing and reviewing policy that promotes sustainable management of geothermal resources.

The Waikato Region contains approximately 80% of the nation's geothermal resources. In developing geothermal policy, Waikato Regional Council has defined geothermal feature types, and then assessed the degree to which they require special efforts at protection based on considerations of rarity and vulnerability. Other aspects of the policy are discussed in a separate paper at this Congress.

Geothermal manifestations on such a scale as occurs in New Zealand are rare in the global context. Waikato Regional Council exercises its stewardship by ensuring a careful balance between often-competing interests in those manifestations, including, where deemed necessary, the interest that certain elements be preserved in as nearly a pristine state as possible.

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 six geysers (Keam, 1988). All the geysers in Geyser Valley, Wairakei, and the Spa, Tauhara ceased action following the establishment of the Wairakei geothermal power station in the 1950s. The formation of Lake Ohakuri in 1961 drowned 50% of the surface features at Orakeikorako including 70 geysers. By 1980 the proliferation of shallow geothermal bores for domestic use in Rotorua city affected the Whakarewarewa geysers, a premier tourist attraction. Many aspects of geothermal systems are thus at risk and it is the responsibility of Waikato Regional Council to ameliorate this within the Region and where possible ensure that mitigation of the effects of past mistakes is pursued.

In this paper we define geothermal feature types and then assess the degree to which they require special efforts at protection based on considerations of rarity and vulnerability. There is no road-map for this process, and the approach is therefore somewhat tentative and subjective - we recognize that alternative, and perhaps improved, approaches could be suggested.

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 feature 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) Pulsating of 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:**
    Cultural, Historical, Economic, Aesthetic, Recreational, Educational, Scientific, and Intrinsic.

2.2 Definitions of geothermal surface features

The types of geothermal features that exist are described and defined in this section. One aim is to identify clearly the types of feature according to the geothermal processes that create and sustain them. Another 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 “sinter-depositing springs”, which in turn are also “geothermal springs and seeps”.

Steam-dominated features:

- **Fumarole:** Any naturally occurring vent, including those found underwater, whose main discharge consists of steam at the local boiling temperature of water and 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 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 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 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 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 deposit around the crater.
- **Geothermally altered ground:** Any 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 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.

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.
- **Sinter-depositing spring:** Any geothermal spring that deposits sinter on surfaces covered by its outflow, or any submerged geothermal spring that would be likely to deposit sinter if it were no longer submerged. The area of a sinter-depositing spring comprises that of the spring basin, together with the area covered by any undiluted liquid outflow from the pool and any sinter deposits created by that outflow.
- **Geyser:** Any 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 the undiluted liquid discharge from the geyser and by any sinter deposits created by that discharge.
- **Spouting spring or perpetual spouter**: A geyser-like boiling spring whose eruption is continuous rather than intermittent.
- **Soda geyser:** A geyser-like feature whose erupting stage is driven mainly by the discharge of carbon dioxide rather than steam.
- **Crypto-geyser:** An 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 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 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. (Only three examples are known to us, two in New Zealand and one in the United States.)

Remnant geothermal water-dominated features:

- **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. (See also Section 2.4 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 habitat:** Any part of a geothermal area that meets the criteria for determining significant indigenous vegetation or significant habitat of indigenous fauna. (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 hotter than 30°C. The area covered by a geothermal wetland, lake, pool, or stream consists of the water body, its bed and banks, any mineral deposits derived from the water body or its outflow, and any thermotolerant, thermophilic, or extremophilic ecosystems dependent on it.

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. In order 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 Geothermal Habitats

Unlike the definitions for other geothermal features, the definition of *Significant Geothermal 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 more modified ones.

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 Habitats according to the plant and animal communities that live in them.

The area of the Waikato Region is approximately 25,000 km^2 (Waikato Regional Council, 1998). The total area of surveyed geothermal habitat in the Waikato Region is minute compared to the region's total land area, and consists of 35 isolated small pockets of land and water, covering no more than 510.21 hectares (5.1 km^2).

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 Habitats are expected to 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.

Eighteen of the Significant Geothermal Habitat features are influenced by both warm ground and geothermal water. Nine are influenced only by warm ground. Three others are influenced only by geothermal water, but support geothermal terrestrial vegetation by virtue of warm air rising from the geothermal water and affecting vegetation growing on cold ground. The remainder are purely aquatic.

Each geothermal feature has a unique set of characteristics such as water or steam chemistry, water depth, temperature, etc. It would be possible to define each item in the habitat class as a unique member of an individual class.

Another option would be to define as members of a separate class only those habitats that were substantially different from others in a particular defining characteristic. For example the geothermal habitat found on the Tongariro system is the only example of a high-altitude geothermal habitat in New Zealand, and supports a uniquely adapted midge. Lake Rotokawa, a geothermal lake with a pH of 2, also has a uniquely adapted invertebrate species, a leech which has adapted to live well outside its normal pH range.

Waikato Regional Council has decided not to define particular unique or extremely rare habitats as separate feature types, because its policies require that all significant feature types be protected equally. Thus from a policy perspective there is nothing to be gained by splitting the habitat class up. However, this does not mean that unique habitats are not more significant than less rare ones, and if particular conservation measures are required, there is no barrier to their implementation.

2.4 Recent sinters and other lost features

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

As a result of geothermal electricity generation the Wairakei-Tauhara and Ohaaki geothermal systems have lost about 20 geysers and 80 boiling springs at Wairakei Geyser Valley, about 6 hot and boiling springs in the Waiora Valley, about 4 geysers at The Spa, perhaps another 5 or 6 substantial springs, which were not geysers, at and near the same place, and 2 geysers and several sinter-depositing springs at Ohaaki.

At Orakeikorako half of the approximately 1000 features mapped have been lost beneath the waters of Ohakuri Lake following the construction of Ohakuri dam and the filling of Ohakuri lake in January 1961 for hydro-electric generation.

Thus 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?

The durable sinter formations that remain after the springs that created them ceased flowing at Wairakei, The Spa and Ohaaki, and that lie submerged beneath the hydro-lake at Orakeikorako, 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.

Not only the "Recent sinters" but also the drowned geysers and other drowned geothermal features at Orakeikorako, 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 need to be counted and included in a total count of geothermal features so that the percentage of geothermal feature types that have already been lost are available for consideration when it comes to applying the results of this analysis to issues of protection and preservation.

3 RARITY AND VULNERABILITY

As will be seen in the following subsections we argue for a particular numerical representation scheme for each of the terms "rarity", "vulnerability to natural changes" and "vulnerability to artificial changes" as applied to each geothermal feature type, and then in due course we shall argue for a way in which these numbers should be combined in order to assess an "endangerment index" for each type. This will be available then for use in defining the degree of protection that such a feature type deserves in order to ensure that New Zealand retains a full range of the different types, and sufficient examples of each type.

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.

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 is: geothermally heated ground or steaming ground; geothermally altered ground; recent sinter; ancient sinter; significant geothermal 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 wholistic approach and defines a terrestrial geothermal habitat to include all occurrences of such habitat within a confined area that is 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 its 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

$$c = k \ln n$$

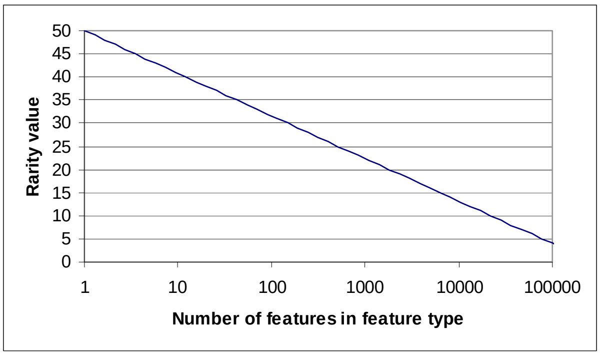
where k is some convenient constant.

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 $k = 4$. 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 250,000, which is orders of magnitude 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.



Graph 1: 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. One possible method of choice is as follows: the Whakarewarewa geothermal area is a compact group of surface features that has been carefully mapped and described. Within a tight boundary surrounding the numbered features one can regard the land surface as being "saturated" with geothermal features, so that every part of the surface lies within the area of one of its numbered features. Thus the average area associated with a single feature is the total area within the boundary divided by the number of features within the boundary. This average turns out to be 635 m^2. We suggest this 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*., 2004 (in press)). We do not yet have detailed lists of other types of geothermal feature in the region, so assessment of their number of occurrences or areas is based on informal lists and local knowledge.

Geothermal springs and seeps require discharge temperatures between 30°C and 100°C (New Zealand legislation defines geothermal water as being above 30°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 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 sinter-depositing springs. Exceptions (See *non-sinter-depositing geyser* in the list of definitions) are a few intermittently erupting features at Ketetahi (Cody *et al*., 2004 (in press)) and 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 144 geysers: 114 in the Waikato Region (Cody *et al*., 2004 (in press)) and approximately 30 at Rotorua and Waimangu in the Bay of Plenty Region (Cody *et al.*, 2002; Lloyd, 1975). Only one in four sinter-depositing springs in the Waikato Region is a geyser (Cody *et al*., 2004 (in press)).

Mud geysers are very rare. They are mud pools with particular thermodynamic and hydro-dynamic eruptive characteristics that set them apart. Four mud geysers are active in the Waikato Region (Cody *et al*., 2004 (in press)), namely one at each of Wairakei, Te Kopia, Waiotapu, and Mokai. 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 is known to us in the U.S.A. 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.

Table 1 lists preliminary figures for geothermal feature types in order of decreasing rarity, with brief comments regarding the reliability of their counts. Final figures will be available in Keam *et al*., (2004, in press).

Table 1: Regional Rarity of Geothermal Features

Feature Type	**Regional Rarity**	**No. in region**	**Comments**
Molten-sulphur producing spring	46	2 -3	Just 2 occurrences known in the Waikato Region, Te Whangi o te Rangi and another hydrothermal explosion crater just downstream of Bridal Veil Falls, both in the Waiotapu Scenic Reserve. It is possible that there is such a spring in a remote area of Te Kopia, Orakeikorako, or Waiotapu.
Mud geyser (subset of Mud pools)	43	5-6	There are 5 known in the Waikato Region, at Te Kopia, Mokai, Wairakei, Orakeikorako, and Waiotapu (Keam *et al.*, in press). It is possible that there is such a geyser in a remote area of Te Kopia, or Waiotapu.
Superheated Fumarole (subset of Fumaroles)	39	15 ± 5	A small proportion of fumaroles emit gases at temperatures greater than 100°C, often in a dramatic pumping action.
Geothermal wetland, lake, or stream	35	40 – 45*	Forty geothermal wetlands, lakes, and streams in the Waikato Region have been listed (Stevens *et al.*, 2003). We estimate that there may be up to 5 unknown sites.
Significant Geothermal Habitat (subset of Geothermally heated or steaming ground, Geothermal wetland, lake, or stream)	35	40 – 50*	There are 35 known significant geothermal vegetation sites in the Waikato Region (Wildland Consultants Ltd, 2004 (in press)). A further 10 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	35	44 – 49*	There are at 44 known sites in the Waikato Region (Given, 1996). We estimate that there may be up to 5 unknown sites.
Geyser Most (but not all) geysers are Sinter-depositing springs)	35	46 ± 5	There are 46 known in the Waikato Region that have not been drowned by the creation of the hydroelectric Lake Ohakuri (Cody *et al.*, in press). 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 Sinter-Depositing Springs category. 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.
Geothermally altered ground	30	150 ± 50 *	Several geothermal collapse pits may occur on an area of geothermally altered ground, so altered ground is estimated to be rarer than collapse pits.
Hydrothermal eruption crater	30	155 ± 50	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. We do not yet have accurate counts of numbers on all geothermal systems. However, the counts for 5 sites have been averaged and extrapolated to cover all geothermal fields that are known to have steam expression.
Recent sinter	29	205 ± 10 *	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 press). There may have been an error of up to ten springs in the documenting of them.
Geothermal collapse pit	27	320 ± 50	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. We do not yet have accurate counts of mud pool numbers at all sites. However, the counts for 7 sites have been averaged and extrapolated to cover all geothermal fields that are known to have steam expression.
Fumarole	26	400 ± 100	We do not yet have accurate counts of fumarole numbers at all sites. However, the counts for 4 sites have been averaged and extrapolated to cover all geothermal fields that are known to have steam expression.
Mud pool	24	650 ± 100	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 Orakeikorako alone. We do not yet have accurate counts of mud pool numbers at all sites. However, the counts for 7 sites have been averaged and extrapolated to cover all geothermal fields that are known to have steam expression.
Sinter-depositing spring (subset of Geothermal springs or seeps)	24	735 ± 50	These include those drowned by the raising of water levels in Lake Taupo and the Waikato River system. 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.
Geothermal spring or seep	21	1525 ± 100	There are 15 large and approximately 30 small geothermal systems known in the Waikato Region. The number of springs on large systems range from 0 to 800. On small systems the range is from 1 to 10. Most springs have been identified fairly well.
Ancient sinter	0 to 20	>2000 *	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, except that we expect they will number at least in the thousands.

* Further consideration may lead to the unit area approach being applied to these entries.

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 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.

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

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 (and incidentally leads to its attractiveness and appeal). 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. Instead we are at present reduced to estimating qualitatively and considering 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 propose a hierarchy of geothermal feature types ordered according to our assessment of their relative average vulnerabilities. This hierarchy is presented in Table 2 below, with explanatory comments included. Where necessary further comments about the entries and their ordering are presented after the table.

3.3 Vulnerability to natural variations and changes

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), 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.

Table 2 below lists the vulnerability to natural influences for each feature type.

Table 2: Vulnerability to Natural Influences

Feature Type	Constraints	Vulnerability
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-geyser or fumarolic activity (respectively) within a restricted type of topographic and geometric environment.	15
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
Superheated 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 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
Sinter-depositing spring	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 collapse, enlargement and coalescence on estimated time scale ~ $10^2 – 10^4$ years.	4
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

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 channeling 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 lists the vulnerability to induced changes for each feature type.

Table 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 and Vulnerability Sum	**Ideal**	**Vulnerability to Fluid Extraction and Reason**	**Vulnerability to Surface Interference and Reason**
Geyser 20-23	No decrease in height, volume or frequency of eruptions	3-4 Fluid extraction causes cessation of flow in geysers.	3 Alteration of sinter formations adversely affects natural eruptive behaviour.
	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.
	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.
Sinter depositing spring 17-21	No decrease in flow rate, 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
	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.
	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 geothermal habitat 16-20	No alteration in fluid flow rate, 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
	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 land extent is not as marked as on sinter springs.	4 Land and surface water drainage reduces extent of features.
	No decrease in extent and undisturbed nature of natural geothermal ecosystems	2-3 Many habitats depend on steam-fed features so effect of ecosystems is not as marked as on sinter springs.	4 Land and surface water drainage reduces extent of ecosystems.
Recent sinter 16-19	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.
	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.
	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.
Mud Geyser 15-17	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.
	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.
	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.
Superheated	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.

Feature Type and Vulner-ability Sum	**Ideal**	**Vulnerability to Fluid Extraction and Reason**	**Vulnerability to Surface Interference and Reason**
Fumar-ole 15-17	No decrease in extent and undisturbed nature of vent and any associated mineral deposits	3 Development may increase steam output to a rate that causes a blow-out.	3-4 Vents can be filled in and deposits removed.
	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.
Fumar-ole 13-16	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.
	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.
	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-thermal wetland, lake, or stream 13-16	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.
	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.
	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 the effect of fluid extraction is similar to that on geothermal springs and seeps.	3-4 Land and surface water drainage reduces extent of ecosystems.
Molten sulphur-produc-ing spring 12-16	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
	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
	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
Geother-mal spring or seep 11-15	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
	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.
	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 ecosystems is not as marked as on sinter springs.	2-3 Land and surface water drainage reduces extent of ecosystems.
Geother-mally heated or steaming ground 10-15	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.
	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.
	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.
Mud pool 12-13	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.
	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.
	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.
Geother mal collapse pit 7-8	No decrease in fluid flow rate, 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.
	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 and Vulner-ability Sum	**Ideal**	**Vulnerability to Fluid Extraction and Reason**	**Vulnerability to Surface Interference and Reason**
	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.
Hydro-thermal eruption crater 7	No decrease in fluid flow rate, 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.
	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.
	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.
Geother mally altered ground 6-7	No decrease in fluid flow rate, 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.
	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.
	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.
Ancient sinter 3-6	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.
	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.
	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 CONCLUSION

The entries for rarity and vulnerability for each geothermal feature type, when completed, will be combined to provide a suitable aggregate. This approach is being used to define Significant Geothermal Features in the Waikato Region, and will guide the Regional Council in determining what uses of particular geothermal systems will be allowed.

The following further work is also required to complete the project:

- More comprehensive counts of surface features
- Analysis of the areas and numbers of extensive features
- An estimate of ancient sinter numbers and extent, based on knowledge on numbers and extent of known occurrences, and numbers of ancient geothermal systems.

REFERENCES

Bryan, T. S., *The Geysers of Yellowstone*. 3rd ed. University Press of Colorado, (1995), 464 p.

Cody, A.D., Keam, R.F., and Luketina, K.M., The geysers of New Zealand, Part 1: The Rotorua geothermal system, *GOSA Transactions*, Geyser Observation and Study Association, U.S.A., 7, (2002), 148-168

Cody, A.D., Keam, R.F., Luketina, K.M. and Speirs, D., *Number and Condition of Sinter-depositing Springs and Geysers in the Waikato Region*, Waikato Regional Council Technical Report (2004, in press).

Given, D. R., *Geothermal Vegetation: an assessment of botanical values*, (Report to Waikato Regional Council June 1996), 19 p.

Keam, R. F.: *Tarawera,* author, Auckland, 1988, xvi, 472 p.

Keam, R.F., Luketina, K.M. and Pipe, L.Z, *Definition and Listing of Significant Geothermal Feature Types in the Waikato Region*, Waikato Regional Council Technical Report (2004, in press).

Lloyd, E. F., The hot springs and hydrothermal eruptions of Waiotapu, *New Zealand Journal of Geology and Geophysics*, **2,** (1959) 141-176 (and especially 155-159)

Lloyd, E. F., *Geology of Whakarewarewa Hot Springs*, DSIR Information Series No. 111, (1975) 24 p.

Lloyd, E. F., *Geology and Hot Springs of Orakeikorako*, New Zealand Geological Survey Bulletin 85, Wellington, 1972, 164 p.

Molloy, J. and A. Davis: *Setting priorities for the conservation of New Zealand's threatened plants and animals*, 2nd edition, compiled by A. Tisdall, Department of Conservation, Wellington (1994).

Stevens, M.I, Cody, A.D., and Hogg, I.D, *Habitat Characteristics of Geothermally Influenced Waters in the Waikato*, Centre for Biodiversity and Ecology Research Report No. 25 for Waikato Regional

Council, University of Waikato, Hamilton, (2003), 122 p.

Waikato Regional Council, *Waikato State of the Environment Report*. Waikato Regional Council, Hamilton, (1998), 244 p.

Waikato Regional Council, *Waikato Regional Policy Statement*. Waikato Regional Council Policy Series No. 00/30, Hamilton, (2000) 172 p.

Wildland Consultants Ltd, 2004: *Geothermal Vegetation of the Waikato Region – Revised 2004*, dated August 2004, Contract Report for Waikato Regional Council (in press)