SUGGESTED CRITERIA FOR GEOTHERMAL FEATURE RANKING AND GEOTHERMAL SYSTEM CATEGORISATION

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ABSTRACT

Geothermal features can be ranked for significance according to various selection criteria. This can assist with assigning geothermal systems to categories based on gradations of desired protection versus development status. Geothermal feature types can be classified by initially separating them into three main groups: active features that are predominantly subject to subsurface fluid management; associated thermal habitats that are mostly the subject of land use management; and remnant features that are also subject to land use controls. Tiered tables of feature types, subtypes and examples, allows for application of ranking values of significance, through assessments of criteria such as rarity and vulnerability to reservoir utilisation. A proposed ranking scheme for categorisation of geothermal systems takes into account five primary criteria (thermal feature types, habitat rarity, landscape values, natural hazards, and access/size constraints).

1. INTRODUCTION

The primary motivation behind this study is to demonstrate that significance ranking of active geothermal features can be accomplished by using a numerical (or similar gradational) scheme that combines consideration of several important criteria. They would include factors generic to the feature type: rarity, stability, vulnerability, and aesthetic value; along with site-specific local factors such as: accessibility, modified setting, utilisation history and cultural value.

When initially undertaking this exercise, it became clear that features that discharge high-chloride (hot brine) fluids are typically considered to be the most vulnerable to reservoir pressure depletion, as well as being relatively rare, and therefore are typically ranked more highly. It also became clear that an objective and agreed method of significance ranking is needed in order to deal with the full range of geothermal feature types and characteristics.

A ranking scheme can also be applied to the task of allocating geothermal systems to different categories to assist with long term resource management at a regional level. For systems that are allocated to 'conditional-protection', or 'protection' categories, rules may be put in place to ensure that any extractive use of energy would have minor, negligible or no impact on the surface environment. For 'conditional-development', 'limited-development' or 'development' categories, appropriate resource management tools may be applied, involving adaptive policies and flexible extraction/injection procedures. Ideally, these should be focussed on outcomes rather than prescriptive methodologies, in order to optimize sustainable energy utilisation, and minimize or remedy adverse effects. Other categories may be needed for lower temperature hot spring aquifers, systems that need more investigation (research), deep sedimentary basins, potential EGS hot rock resources, etc.

This paper is a discussion document. It is based on many debates held over the past decade with geothermal colleagues (mostly fellow scientists, planners and lawyers), in connection with preparing submissions for the process of establishing and reviewing Geothermal Policies and Plans (under the Resource Management Act) for the Waikato Regional Council (Bromley, 2003, 2004, 2005, 2006) and more recently for the Bay of Plenty Regional Council (Bay of Plenty Regional Council, 2010, Bromley, 2011).

2. POLICIES ON FEATURE SIGNIFICANCE

Maintaining conditions that support overall system pressure and temperature is the recommended policy instrument for protected or conditionally protected systems. Such systems are categorised, in part, on the basis that they contain many highly-ranked, discharging, significant geothermal features with the chemical characteristics of a deep geothermal fluid (usually 'hot brine'), and that such features are more vulnerable to deep pressure changes induced by reservoir fluid extraction and injection operations. In the case of development and conditional development systems, an adaptive management regime is appropriate. This includes targeted (or locally applied) pressure and temperature management, if required. Such systems have lower ranked features, typically with reduced vulnerability.

Problems have been encountered in the past when interpreting policies that use the adjective "significant" with respect to geothermal features and habitat or as a measure of the severity of an adverse surface environmental effect. In practice, a degree of significance is implied but is not always objectively applied. Establishing cause and effect of observed changes can also be difficult, particularly where natural variations are large and long term natural changes are poorly known. Another concept that can be difficult to deal with, in practice, is the principle of "like-for-like remediation" for induced thermal feature changes. It is generally agreed that some incentives are appropriate for remediation schemes through localised subsurface pressure management. Such schemes could conceivably result in newly active or restored natural geothermal features. But not all such features would necessarily be the same, in terms of feature type, to those that were adversely affected in the past. However, adopting a holistic approach to the value of geothermal features in general, such 'remediation' efforts would still be encouraged.

2.1 Feature type definitions

A list of all geothermal feature types is useful for the purpose of assessing degrees of significance, rather than relying on a list of 'significant' geothermal feature types.

A list of feature types, which is subdivided into 'active thermal features', 'geothermal habitats' and 'remnant landforms', assists with differentiating between management responses required to deal with possible vulnerability to 'reservoir changes', 'thermal discharge changes' and 'land-use changes', respectively. Such a list is provided in Table 1. The application of policies that focus on resource issues related to fluid management can then be separated from those that deal more with land-use control (using terrestrial features criteria) and ecosystem issues (habitat protection).

In Table 1, the features are grouped according to type and subtype, followed by examples and a simple description. This tree structure lends itself to further subdivision, if desired, to accommodate other subsidiary feature types or features of mixed origin. Some subdivision ranking within feature types is also appropriate. To take an example from the table, the term 'geyser' is a broad feature type that has several subtypes with respect to scale, driving mechanism, and relative significance. One subtype example, a small 'crypto-geyser', could otherwise be described as a 'boiling spouting spring' (eg. 'Ngararatuatara' cooking pool at Whakarewarewa, Rotorua), and is a more common and correspondingly less significant subtype than a true geyser with large cyclic discharges (such as 'Pohutu', Te Puia, Rotorua).

2.2 Habitat and landform feature types

Geothermal habitat types and remnant geothermal landform features are grouped, listed and described separately in Table 2. As examples of the landform category, 'recent sinter' and 'hydrothermal eruption craters' are geological features, remnants of past geothermal features. Because they are not currently associated with actively discharging thermal vents, they are not considered for significance ranking in terms of geothermal fluid management. Such features may, however, be considered for significance with respect to land use activities and through application of 'terrestrial features criteria' for significance ranking. If, in the future, they become re-activated or restored, they would then be re-categorised as actively discharging thermal features and different significance criteria and management rules may then apply.

Geothermal habitat types, as listed in Table 2, are broadly associated with different discharging thermal feature types. Again, the list lends itself to further subdivision if desired. Because such habitats are derived from, and dependent upon, the discharge of heat, fluid or chemicals from thermal features, they may be regarded as 'characteristics' or 'attributes' of thermal discharges in terms of management policy. Habitats can be ranked on site-specific criteria, allowing for appropriate protection measures (such as fencing, weed control and construction stand-off distances) from potential adverse effects caused by land use activities.

Geothermal eco-systems, while being generally adaptive and resilient to relatively large natural changes in thermal discharges, are highly valued attributes of the geothermally-influenced surface environment, and some degree of protection from adverse effects is often sought after by environmental policy-makers. A common miss-perception, however, is that large-scale geothermal utilisation necessarily causes a long-term reduction in geothermal habitat, and hence indigenous thermal vegetation commonly found in New Zealand, such as 'prostrate kanuka', is thought to be "at risk of decline". In reality, large areas of this type of vegetation associated with steam-heated ground have benefited from development-induced subsurface boiling which has increased the flux of steam to surface features, allowing colonisation by thermal vegetation. Arguably, greater risks are posed to such vegetation from browsing animals, road construction and fires. These risks are best managed through land use measures rather than resource use measures.

On the other hand, some geothermal habitats are dependent on steady hot spring discharges (such as the frost-free micro-climate along the banks of thermal streams, favouring the establishment of tropical ferns in subtropical regions). Here, efforts to maintain surface discharge through injection management can help sustain both the hot springs and their attributes such as the associated plant communities. In this case, an avoid-remedy-mitigate approach is probably most appropriate, bearing in mind that some induced changes are possible in a development system, but monitoring and adaptive injection management can provide a means for remedying observed adverse effects on such features.

3. SIGNIFICANCE ASSESSMENT CRITERIA

To assist with ranking thermal features, various tests for significance can be applied. Where surface thermal features are relatively common, have relatively low aesthetic and scientific value, or have been significantly modified by human activity, they would be expected to have a relatively low ranking. Where the features are relatively rare, but accessible and well known, they might have a higher value from the public's perspective. Where the features are of a type that are prone to significant natural variation with time, including vent erosion and rainfall effects, they might have a lower value from the point of view of sustainability.

In Table 3, an example is provided of how such criteria could be applied through application of a numerically-based ranking scheme. The choice of ranking numbers (1 to 4) is somewhat arbitrary and a similar outcome could be achieved by applying other grading schemes (e.g. shades of grey, or letters). The main purpose of this table, however, is to illustrate how an objective assessment approach could be undertaken. In this approach, a set of criteria allows for ranking of thermal features into four categories ("outstanding", "highly", "moderately" or "lowly" ranked), depending on four criteria related to the feature type (rarity, stability, vulnerability, aesthetics) and one criterion which combines four local site-specific factors (accessibility, degree of modification, utilisation and cultural values).

The numerical ranking scheme was developed from a set of queries for ranking geothermal features. They establish the degree to which feature types are:

a) Rare, in the regional context (eg. Taupo Volcanic Zone (TVZ) geothermal region)?

b) Naturally stable or resilient?

c) Vulnerable to pressure decline (brine type)?

d) Visually or aesthetically spectacular?

The ranking scheme also establishes the degree to which individual features or groups of features are considered valuable from a local or site-specific point of view. Queries include the degree to which features are:

a) Accessible and known to the public?

b) In an unmodified or modified setting?

c) Of historic or existing utilisation value?

d) Of importance with respect to cultural value?

3.1 Rarity and stability

Rarity is a relative parameter and needs to be expressed with respect to the wider geological region within which the geothermal systems are hosted, for example the TVZ. A rarity assessment may be difficult to achieve using simple counts of the number of individual thermal features, because those numbers depend on the minimum size criteria applied to the feature count. In many cases, a comparison of areas of thermal ground using infra-red surveys, or associated thermally tolerant vegetation is more appropriate.

Natural stability, as a significance criterium, has previously been argued as an important parameter for discriminating geothermal feature types with diverse physical characteristics (Bromley, 2003-2006). Some features are highly variable, ephemeral or transitory in their natural state (such as steam vents or mud-pools), while others are typically more stable (such as high chloride springs). Flows from mixed and steam-heated groundwater springs are typically susceptible to long-term rainfall variations. It is not realistic to expect to be able to preserve all of the discharge characteristics of transient thermal features that are naturally highly variable. So, significance ranking for resource management purposes needs to take into account the natural variability as well as the inherent resilience of the feature type.

3.2 Vulnerability to extraction

Extraction and injection of fluid from a geothermal system will inevitably cause local pressure changes in the reservoir, even if all the extracted fluid is re-injected. Those pressure changes will, in turn, generate additional inflows or outflows of fluid from surrounding recharge aquifers (whether adjacent, above or below the reservoir). In some cases, these pressure changes may have no discernable effect (within natural variations) on surface thermal features, but, in other cases, they could have some influence on the quantity of heat, fluid, steam and gas rising to the surface. These induced changes could cause a surface discharge increase (from production-induced boiling of an underlying liquid zone, or a local pressure rise associated with injection). Alternatively, they could cause a surface discharge decrease (from production-induced pressure decline in a shallow steam zone or from saturation of shallow steam by liquid injection). Such effects have been observed in thermal areas in development geothermal systems in the TVZ. Overall, the possible induced effects (discharge increases and/or decreases) should be considered in the context of the background natural variability of discharge parameters.

Vulnerability assessment also takes into account the knowledge that induced changes are not necessarily permanent. Where appropriate, such changes can often be reversed by adjustments to injection and production strategy. Examples of this have occurred at several geothermal systems in the TVZ, including Rotorua, Mokai and Rotokawa.

All of these considerations are incorporated in the proposed ranking scheme summarised in Table 3. Figure 1 illustrates the histogram of rankings of the 18 geothermal feature types, according to the four generic criteria, along with a combined (average) histogram. When applying this method to actual features (rather than feature types) the average value would also incorporate an extra criterion which would itself be calculated using an average of several site-specific factors. Table 4 provides some specific examples by ranking four different geothermal features in the TVZ.

4. GEOTHERMAL SYSTEM CATEGORISATION

Sustainable management of a region's geothermal resources can be achieved through allocating the identified geothermal systems into categories suitable for various levels of protection, research or development. The criteria for categorising the geothermal systems should be designed to provide for development of those that are suitable for utilisation in an environmentally prudent manner, while protecting other systems, based on their outstanding natural characteristics. Systems that are poorly delineated or under-explored will require further investigation before they can be properly categorised (a research category). Others should only be developed with some degree of caution (perhaps using a staged development approach) in order to avoid excessive adverse effects, whilst learning about the response of the surface environment to subsurface pressure changes ('limited' or 'conditional-development' category). Other categories may be needed for: low-enthalpy hot-spring resources of tectonic origin; deep sedimentary brine aquifers of moderate temperature; and deep hot-rock resources in conductive temperature regimes, suitable for development as Enhanced Geothermal Systems.

The difficulty with the regional allocation process is in setting an appropriate level of system protection. This has changed with time. Over the past few decades new knowledge has been acquired (and will continue to be so) that allows for better management of resources, particularly using methods for avoiding or remedying adverse effects on surface features, while sustaining energy extraction. Over the past 10 years, for example, adaptive management of surface effects through adjustments to injection strategy has become an acceptable policy instrument, because of knowledge acquired from monitoring during operation of developed geothermal systems. The 'remedy' option has become more robust with time.

System classification is dependent initially on an assessment of system temperature. A convenient subdivision into high (>200 ^oC), moderate (100-200 ^oC) and low (<100 ^oC) temperature ranges, based on chemical geothermometry or measured borehole temperatures, allows for an initial assessment of the system's potential for large scale electricity generation, direct use or small-scale bathing and heating applications. The next consideration is the significance of geothermal surface features and associated ecologies, including their vulnerability to extractive uses. Finally, there should be consideration of any existing use and future development potential. An important aspect is the identification of active thermal features that depend on discharges of high-chloride water from depth, and the ranking of them in terms of significance, because these features are generally the most vulnerable to subsurface development and are typically rarer and higher in perceived value. Management of effects on remnant features and thermo-tolerant vegetation are principally about controlling competing land uses, and these need a different set of criteria for ranking.

The process of allocating systems to different categories invites consideration of several other criteria in addition to the significance ranking of the natural surface geothermal features and their habitats. Consideration should also include landscape values (a relative measure of the urban, rural or pristine natural setting of the geothermal system). Also, leaving aside any legal arguments as to the scope of regional environmental policies and plans to consider the bigger picture, and taking instead a holistic approach, other criteria for system categorisation should also include the potential size of the resource, and its ease of access and proximity to an energy demand centre or grid connection. These criteria affect its potential for economic utilisation. If accessible and large, the resource could potentially contribute significantly to achieving, in New Zealand's case, its 90% renewable electricity target, and net reduction in carbon emissions, thereby providing a global environmental benefit. If the prospect is less accessible and small, the potential environmental benefits are consequently reduced, and the merit balance swings in favour of preservation. Other criteria worthy of consideration include: potential hazards from anticipated fluid and gas chemistry, volcanic risk, subsidence and earthquake risk, and potential impacts of development on existing communities, other resource users, neighbouring systems, groundwater users and tourism operators.

The proposed geothermal system assessment and ranking scheme, for the purposes of categorisation, incorporates a similar numerical grading scheme to that used for feature ranking, whereby an average grade is calculated from five criteria. For each system these are graded 1 to 4, where a '1' contributes towards development category and a '4' contributes towards protection category. The five criteria are listed below:

a) Geothermal feature significance (incorporating site specific factors);

b) Geothermal habitat rarity;

c) Landscape values: urban, rural or pristine natural setting;

d) Potential gas, subsidence, eruption or earthquake hazard; and potential interference risks;

e) Access and size constraints: potential for climate change mitigation.

It is proposed that the five criteria be weighted equally, and that the grading factors are applied in such a manner that the systems end up being distributed reasonably equally across the various categories between development and protection. New information, in the future, will provide more details on the subsurface temperatures, boundaries, system fluid linkages and resource characteristics of the systems. The possibility exists of potential fluid linkages or connections between neighbouring systems. Evidence for pressure interference between such systems may not be demonstrated for years or even decades following commencement of significant fluid extraction. However, it does mean that measures may be needed in future to ensure that development of one system does not cause significant effects that are inconsistent with the management purposes for the neighbouring system.

For systems where the uncertainties are greatest, the appropriate category, initially, is 'research', but as knowledge is acquired these systems will be re-classified into different categories. An efficient process to allow this to occur needs to be established when the systems are first allocated. Also, research activities to test reservoir behaviour may include deep drilling and discharge testing, including long-term flow tests. Therefore it would be appropriate to anticipate permit applications for such activities before categorisation of these systems is finalised.

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Table 1. Active geothermal feature types

Type	*Subtype*	*Examples*	*Description*
Water-dominated	Springs	Alkaline chloride	highly mineralised, vigorously deposits sinter
		Acid chloride	mixed shallow acid and deep chloride
		Acid sulphate	shallow origin (oxidised H_2S and steam)
		Bicarbonate	steam-heated water
		Spouting	vigorously boiling and overflowing
		Mixed origin	various origins, diluted by groundwater
	Geysers	Cyclic/intermittent	relatively large discharge, >1 m height
		Crypto-geyser	relatively small, intermittent spouter
		Soda-geyser	driven by CO_2 discharge rather than boiling
Steam-dominated	Fumaroles	Super-heated	large flowrate and noisy emission
		Boiling temperature	typical, atmospheric-pressure steam vent
		Sulphur depositing	relatively high H_2S, steam vent
	Mudpools	Non-discharging	typical, steam-heated pool, often turbid
		Mud-volcano	spouting mud splatter, builds cone
		Erupting / geysering	intermittent, steam-fed, large, violent
	Steam-heated Gnd	Minor fumaroles	small, irregular, transient, steam vents
		Diffuse steam	weak, diffuse emissions, not always visible

Table 2. Geothermal habitats and remnant (landform) features

Landform Type	*Subtype*	*Examples*	*Description*
Water-deposited	sinters	recent	historically active but now dormant features
		epithermal sinter	old sinters from pre-historic discharges
Steam-generated	collapse pits	thermal tomos	old depressions in cooled steam zones
	hydrothermal alteration	recent clay	historically active but now dormant features
		epithermal clays	pre-historic thermal clay deposits
Boiling eruption	hydrothermal eruption craters		dormant or extinct hydrothermal eruption vent
Habitat Type	*Subtype*	*Examples*	*Description*
Thermal Vegetation	hot soil	normal pH	prostrate kanuka scrubland
	cooled soil	acid pH	prostrate kanuka scrubland
	thermal micro-climate	low temp./gas	tropical (frost-sensitive) ferns
		high temp./gas	mosses on steaming ground
	wetland/pond	thermal swamp	thermal swamp vegetation (eg ferns)
Fauna	aquatic	fish, snails	tropical fish, arsenic-tolerant snails, etc.
	insects	flies	feed off algae mats, etc.
Microbes	bacteria	thermophyllic	tolerant of thermal mineralised water
		acidophyllic	tolerant of acid fluids

Table 3 Ranking criteria, using numeric parameters, for active geothermal feature types :
4 = outstanding, 3 = highly-ranked, 2 = moderately-ranked, 1 = lowly-ranked

Feature Type	*Rare type*	*Naturally Stable or Resilient*	*Vulnerable to liquid pressure decline*	*Visual appeal, aesthetic value*	*Generic Average (1-4)*
Hot Springs					
Vigorously sinter-depositing chloride springs	3	4	4	3	3.5
High flow alkaline chloride springs	2	4	4	2	3
Spouting springs	2	3	3	3	2.75
Acid chloride springs	3	2	3	2	2.5
Acid sulphate springs	2	2	1	2	1.75
Bicarbonate springs	1	2	1	1	1.25
Mixed origin springs	1	2	2	1	1.5
Geysers					
Cyclic/intermittent geysers	4	1	4	4	3.25
Crypto-geyser	3	2	4	3	3
Soda-geyser	3	2	3	3	2.75
Fumaroles					
Super-heated fumaroles	4	3	1	4	3
Sulphur depositing fumaroles	3	2	1	3	2.25
Boiling temperature fumaroles	2	2	1	2	1.75
Minor fumaroles / steaming ground	1	1	1	1	1
Diffuse steam	1	1	1	1	1
Mud Pools					
Mud-volcano	2	1	1	4	2
Erupting mudpools	3	1	1	3	2
Non-discharging mudpools	1	2	1	2	1.5

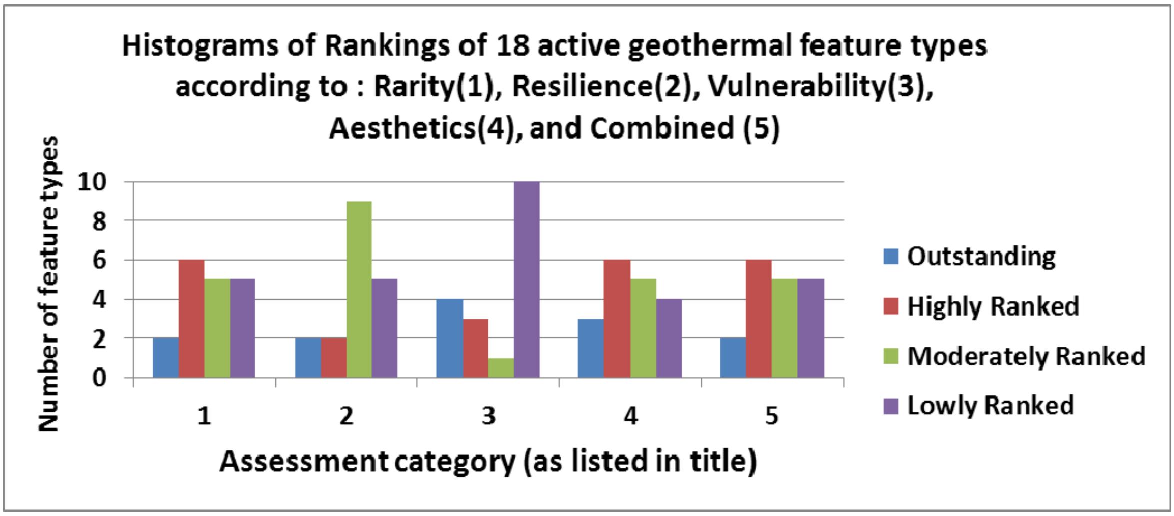

Figure 1: Histograms of rankings of geothermal feature types per category and as an average (combined). This shows that the outcome (without site-specific considerations), is a reasonably even distribution.

Table 4. Example of proposed ranking method applied to specific geothermal features in the TVZ. Site specific criteria (shaded) are assessed separately and the result averaged with the first four generic factors (combined ranking).

Feature name	Feature type	Rarity	Resil-ience	Vulner-ability	Aesth-etics	Access-ible	Un-modified	Historic	Cultural	Site-specific	Com-bined
Pohutu	geyser large	4	1	4	4	4	3	4	4	3.75	3.35
Parimahana	diffuse steam	1	1	1	1	1	4	1	2	2	1.2
Ketetahi	fumarole superheat	4	3	1	4	3	4	3	3	3.25	3.05
Butchers Pool	spring bicarb.	1	2	1	1	4	1	3	1	2.25	1.45