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Geothermal Surface Feature Catalogue of New Zealand: Implications for Geothermal Development in New Zealand

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ABSTRACT

Geothermal surface features are the surface expression of geothermal systems. Geothermal surface features have many unique and sought-after values. These values include cultural (e.g. bathing, cooking, spiritual), economic (e.g. tourism, heating), landscape, scientific and biodiversity. In New Zealand the presence of surface features is used to help classify geothermal systems for appropriate levels of use or protection. Their values are also assessed by resource managers as development occurs – finding the balance between protecting these values and enabling developments that may have adverse effects on these features. A key question for any developer and resource manager is "How important are these geothermal surface features and what are the effects that these values are most vulnerable to?"

Understanding the overall extent, distribution and type of features is therefore fundamental to management. A catalogue of over 5000 geothermal surface features is compiled for New Zealand from published reports and includes both high temperature and low-temperature geothermal features from 35 geothermal fields. The catalogue uses an established method of classifying types of geothermal surface features that enables it to be searched and sorted rapidly.

The catalogue includes most known geothermal surface features in New Zealand and is large enough to enable a statistical analysis of geothermal surface features in New Zealand and their physical characteristics such as water temperature and flow rates. This provides an opportunity to compare characteristics of geothermal surface features at a national-scale, and be used to identify features that could be considered an outstanding example of their type in New Zealand. It also supports resource managers in considering the effects of activities, and an appropriate management response, whether this be protecting features by avoiding adverse effects, or enabling development around other features.

1. INTRODUCTION

The New Zealand Resource Management Act (1991) (RMA) requires national, regional and local authorities to manage the use, development and protection of natural and physical resources in a sustainable way that safeguards the life-supporting capacity of ecosystems and avoid/remedy or mitigate any adverse effects of activities on the environment. Under the Act regional councils manage the taking and use of geothermal water and heat and managing geothermal discharges to the environment. Overall guidance is through regional policy documents and implementation through regional plans. Use of the resource is through resource consents (ie. permits). Councils also monitor and report on the overall state of the environment, including the state of geothermal surface features.

Applying the RMA in geothermal applications has seen regional councils (namely, Bay of Plenty Regional Council (BOPRC), Waikato Regional Council and Northland Regional Council) assess consent applications for use of the resource. Councils may grant or decline an application and set conditions on a resource consent to avoid remedy or mitigate any adverse effects and for monitoring of effects over the life time of a consent. Applications for use will consider a wide range of effects, including overall reservoir sustainability and effects on surface features. The type of assessment will reflect the scale of the activity and magnitude of any potential adverse effects (i.e. with a greater level of scrutiny for large developments such as power plants). This process makes it important for both the developers and the authorities to have sufficient, reliable data that can be assessed using proven methodologies to assess the effects of a development on geothermal resources.

While all surface geothermal features have value, understanding which are most significant and the effects that they are most vulnerable to is helpful when considering what activities should or should not be allowed. For example, some are more vulnerable to changes in temperature and pressure and others to land use activities such as earthworks, damming and diversion.

Historically, this assessment has been done in New Zealand through expert opinion, relying largely on the experience and knowledge of geothermal experts assessing probable effects associated with the proposed activity. Methods of standardising this assessment have been proposed that include making assessments at a geothermal-field scale through to individual surface features scale assessments (e.g. Scott and Bromley 2017, Scott et al. 2018, Keam et al. 2005). In all cases, knowledge of existing geothermal surface features (i.e. a catalogue) and their perceived importance to culture, science and society is required in the New Zealand setting.

Early geothermal catalogues in New Zealand were developed by Houghton et al. *(*1980) who identified 88 hydrothermal systems in New Zealand. This was further developed by Houghton et al. (1989) to obtain an 'Inventory of New Zealand Geothermal Fields and Features' which lists 146 geothermal fields and features. Keam et al. (2005) summarises the number of geothermal features in the Waikato Region divided into 16 active feature types as part of a larger study assessing the significance of geothermal features for the regional authority. A similar database was used to assess geodiversity of geothermal fields in the Taupo Volcanic Zone by Cody (2007). In all cases, either only a selection of geothermal features is used, or, the source of the raw data is unknown.

Internationally, catalogues of geothermal surface features are integrated into larger geothermal databases that can also encompass bore hole data, production data and chemistry data (e.g. Sonney and Vuataz 2008; Muraoka et al. 2010; Trumpy and Manzella 2017; Hauksdóttir et al. 2005). These databases are generally used to promote data to developers, researchers and resource managers and have more of a focus on down hole attributes rather than surface feature attributes and appear to be static (i.e. not time dependent) with relation to their surface feature data (which can change over time).

This paper describes how a catalogue of geothermal surface features in New Zealand is constructed and describes the catalogue's relevance to resource management in New Zealand that could be used in a world-wide context. We present a catalogue that has been constructed using standardised terminology from a large range of data sources that targets resource managers, consultants, researchers and the general public.

2. METHOD

Publicly available data from over 144 published and unpublished reports, and databases is used to construct a geothermal surface features catalogue for New Zealand. Data obtained for each geothermal surface feature conforms to the "New Feature" data requirements and conventions (where possible) in the monitoring geothermal field feature guidelines described in Scott (2012) which enables standardisation so that the data can be compared and searched in a robust manner.

Data recorded for each feature includes the location, field measurements (such as water temperature, flow), physical description, date of the measurement/observation and associated metadata (e.g. methods, errors). Each feature was assigned one of the 12 feature types as described in BOPRC (2014) and Scott (2012) (Figure 1). The minimum data requirements for a record were geothermal field, location, feature type and an observation date.

Interpretation of feature types was required given that much of the data used to make the catalogue predates the standards used in this paper. Four factors were considered when assigning a feature type:

- Description and/or photograph of the feature from the report.
- The pH of a water feature was used to differentiate between a primary (pH ~6 – 9) and mixed feature (pH 1-6, 9-12) where the pH information is available.
- If a hydrogen sulphide smell is described at a water feature, assign a mixed feature.
- Authors knowledge of the feature and / or expected feature type based on knowledge of the geothermal system.

There is also a high degree of variability in the quantity and quality of data available given that the data were collected for a variety of purposes, by different organisations over a long period of time with different standards. Guidelines we use to standardise the data include:

- All locations use latitude and longitude (WGS84 Datum) as transcribed from the relevant report/map. In some cases, Google Earth imagery is used to refine the location of some features based on identifiable attributes (e.g. hot pool, bare ground) in the Google Earth image.
- Location errors are estimated. This will generally depend on the perceived accuracy of the location data. This may include detailed maps (with estimated errors of ±5 m) through to regional maps/grid coordinates (with estimated errors of ± 100 m).
- Feature association with geothermal fields were estimated from maps based on published and unpublished geothermal field boundaries. Where geothermal features were outside accepted geothermal field boundaries:
    1) The geothermal surface feature was assigned to the nearest geothermal field for high-temperature geothermal fields.
    2) The geothermal surface feature was assigned to a generic "Small Systems" geothermal field. This geothermal field generally encompasses almost all low-temperature geothermal systems and covers all New Zealand (i.e. is not geographically constrained like the other geothermal fields).

Time-based feature observations were also included in the catalogue. This occurs where multiple studies have been made in specific areas, usually by different authors. The most recent observation at a feature is used because the focus of this work is to present a snapshot of geothermal surface features in New Zealand. This requires two additional "Feature type" categories to be established: "No thermal activity" – where thermal activity has ceased at a thermal feature, and, "Cannot be located" – where a feature cannot be located (possibly due to changes in land access or land use). These two additional categories cannot distinguish between features that are dormant or extinct – a factor that could influence future assessments of significance e.g. a geyser that has not erupted for a long period of time (and recorded as "No thermal activity") may not have monitoring data and will impact the statistical assessment.

Table 15 - Geothermal features : main types and associated habitats				
Discharge energy High ↕ Low	1. Geysers	4. Intermittent or active hydrothermal eruption craters	7. Mud geysers	10. Fumaroles
	2. Flowing springs	5. Mixed springs	8. Ejecting mud pots	11. Steaming ground
	3. Non flowing pools	6. Mixed pools	9. Mud pools	12. Heated ground
	Primary geothermal fluid	*Mixed/diluted geothermal fluid*	*Mixed/diluted steam heated fluid*	*Steam Fed*
Geothermally-influenced aquatic habitat				
Geothermal habitat on heated/acid dry ground				
Habitat dependent on geothermally-altered atmosphere overlays all types (warm air, frost-free)				

Figure 1. Geothermal surface feature types as described by BOPRC (2014). Note that these are the same feature types in Scott (2012) except the "Hydrothermal Eruption Crater" feature type (inside the red box) that is NOT in Scott (2012) (from BOPRC 2012).

3. RESULTS AND DISCUSSION

5122 geothermal surface features from 35 geothermal fields in New Zealand are catalogued using publicly available data. Feature observation dates range from before 1920 to 2019, with many observation dates having to be estimated. 4578 features are considered to be active (i.e. can be found and have thermal activity) at the last time they were documented.

The most common geothermal feature types are mixed fluid features (pools and springs) followed by primary flowing springs which account for over 41% of the total number of features. The rarest feature types are mud geysers and geysers (Table 1, Figure 2). The Rotorua, Orakeikorako, Wairakei and Waiotapu Geothermal Fields have the most mapped features (Figure 3), with only Rotorua and Wairakei having at least one of every type of feature. These four geothermal fields account for over 63% of the catalogued geothermal surface features in New Zealand, and include protected, limited development and a development geothermal field (Wairakei). It is likely that the number of active geothermal surface features from the developed Wairakei Geothermal Field is outdated given that most of the data was collected in the predevelopment and/or early after commissioning stage (1950's) where the response of the surface features to fluid extraction may have been small. Outdated data is considered a key limitation of this catalogue and needs to be recognized when using the catalogue for management decisions. This is more likely to be an issue in geothermal fields where large-scale development has affected geothermal surface features.

Small geothermal systems account for 231 active features and are mapped in 11 of the 16 geothermal regions of New Zealand. The wide distribution of these features throughout New Zealand is linked to heat sources caused by both volcanism and plate boundary (tectonic) mechanisms (Reyes et al. 2010). Most features from small systems are classified as mixed flowing springs.

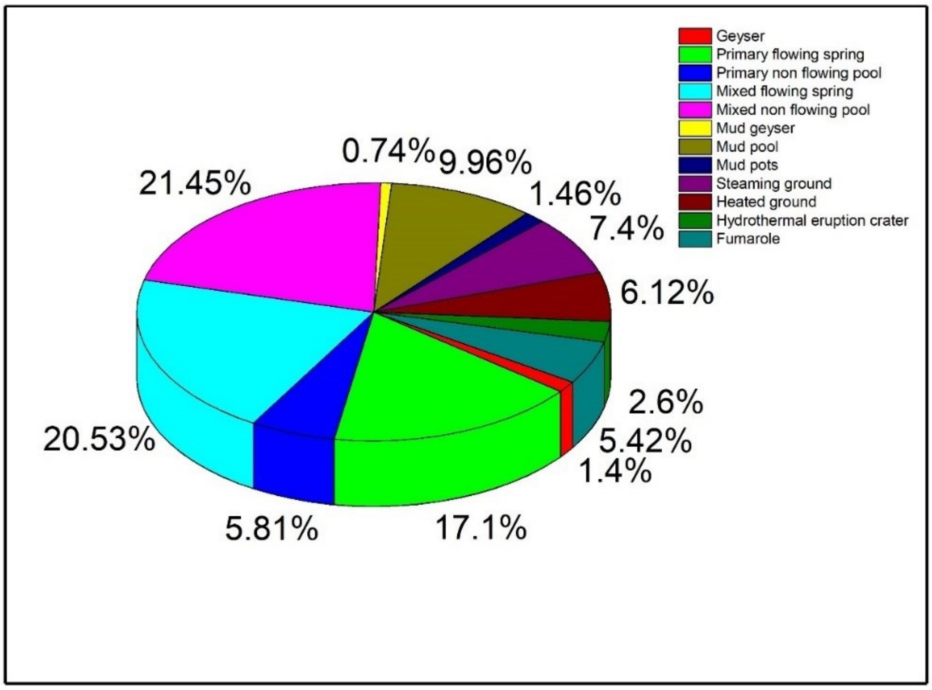

Figure 2. Percentage of geothermal feature types for active geothermal surface features in New Zealand.

Geothermal Field	Region	Field classification	Surface Area (km^2)	Geyser	Primary flowing spring	Primary non flowing pool	Mixed flowing spring	Mixed non flowing pool	Mud geyser	Mud pool	Mud pots	Steaming ground	Heated ground	Hydrothermal eruption crater	Fumarole	Grand Total
Rotorua	Bay of Plenty	Limited Development	12	9	261	44	191	453	19	194	46	103	132	20	33	1505
Tikitere	Bay of Plenty	Development	10		3		78	80		4	1	11	7	10	3	197
Waimangu-Rotomahana-MtTarawera	Bay of Plenty	Protected	18*	7	82	2	21	2				28	6	3	8	159
Kawerau	Bay of Plenty	Development	12		18	9	14	1			1	38	29	6	14	130
Taheke	Bay of Plenty	Limited Development	2				21	10				13	3		3	50
White Island (Whakaari)	Bay of Plenty	Protected	4.8				12	3		1		1	2		16	35
Rotoma-Tikorangi-Mangakotukutuku	Bay of Plenty	Limited Development	16*		8		9					1	2		3	23
Whale Island	Bay of Plenty	Protected	1				5					4	2		8	19
Lake Rotokawa-Mokoia	Bay of Plenty	Limited Development	18.4*		12		1	1					1			15
Mayor Island	Bay of Plenty	Limited Development	1*				2									2
Lakes Okataina-Tarawera	Bay of Plenty	Protected	2*		2											2
Centre basin – Rotoiti	Bay of Plenty	Limited Development	9.3*		1											1
Awakeri	Bay of Plenty	Limited Development	6*				1									1
Ngawha	Northland	Development	10*				25	42	3	4			2		14	90
Small systems	Various	Limited Development	N/A		6		171	22	1	1		1	3		10	215
Orakeikorako	Waikato	Protected	12	40	260	143	11	20	1	104		5		16	15	615
Wairakei	Waikato	Development	15	2	61	25	89	134	6	55	5	35	2	17	23	454
Waiotapu	Waikato	Protected	17	4	10	25	105	35		45	5	20	46	25	11	331
Tongariro	Waikato	Protected	4				25	21		12		30			56	144
Rotokawa	Waikato	Development	10				25	62		1		34	17	1		140
Taupo-Tauhara	Waikato	Development	20			4	13	49		7		1	10	3		87
Waikite	Waikato	Protected	5				48	4			4	3	8	8	6	81
Tokaanu	Waikato	Limited Development	9.5	2	32	11	5	7		1	4	7				69
Te Kopia	Waikato	Protected	15				7	16	2	14		1		5	7	52
Mokai	Waikato	Development	40				34		2	9		1	1		4	51
Ngatamariki	Waikato	Development	7		27	3	1	2		1				1		35
Broadlands (Ohaaki)	Waikato	Development	15				1	11		1	1		6	2	6	28
Reporoa	Waikato	Research	15				6	6				2			6	20
Mangakino	Waikato	Development	6				7								1	8

Geothermal Field	Region	Field classification	Surface Area (km^2)	Geyser	Primary flowing spring	Primary non flowing pool	Mixed flowing spring	Mixed non flowing pool	Mud geyser	Mud pool	Mud pots	Steaming ground	Heated ground	Hydrothermal eruption crater	Fumarole	Grand Total
Atiamuri	Waikato	Limited Development	8				4			2				1		7
Whangairorohea	Waikato	Limited Development	0.005				2	1						1		4
Horomatangi	Waikato	Protected	0.5				2						1		1	4
Horohoro	Waikato	Development	1				3									3
Ruapehu	Waikato	Protected	0.5				1									1
Total				**64**	**783**	**266**	**940**	**982**	**34**	**456**	**67**	**339**	**280**	**119**	**248**	**4578**

Surface area from Cody (2007) or estimated by the authors*

Table 1. Summary of feature types at each geothermal field for active features.

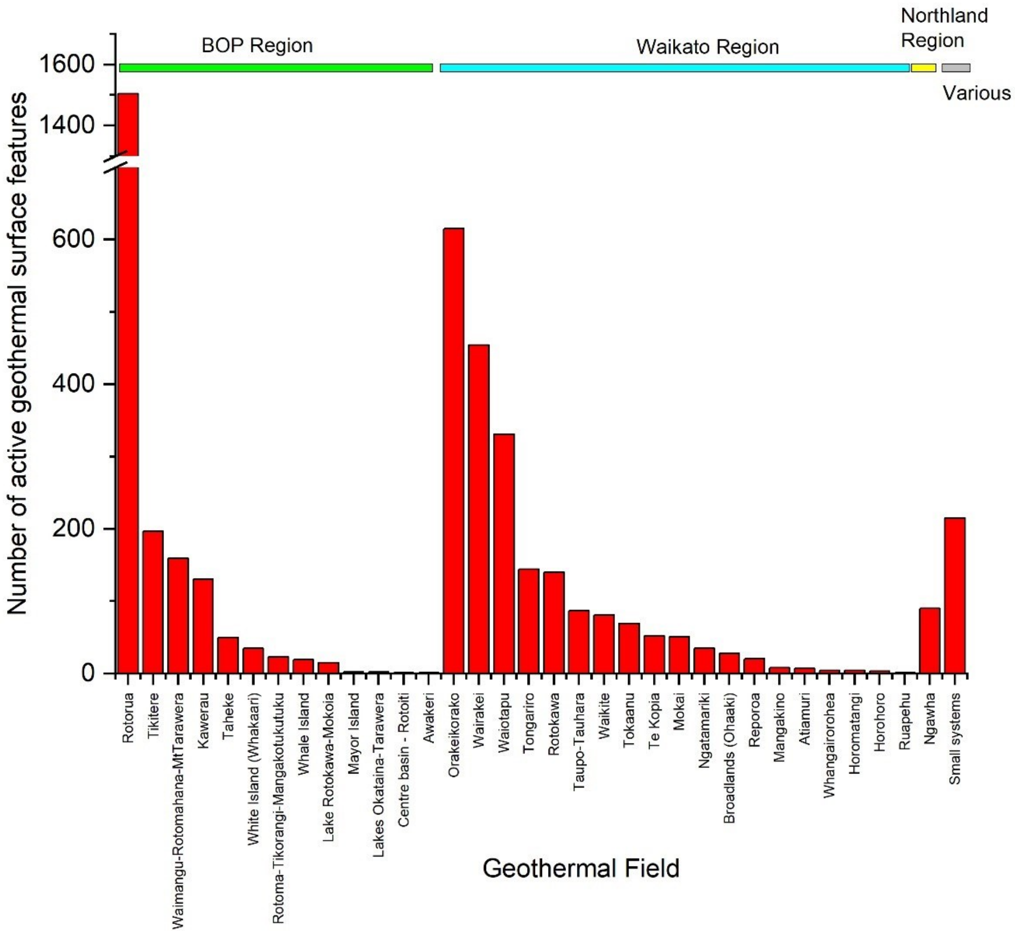

Figure 3. Number of active geothermal surface features at each geothermal field in New Zealand.

Feature size, temperature and flow (for primary and mixed springs only) for available features is compiled with statistical parameters presented in Figures 4, 5 and 6 respectively. The size of the feature provides an indication of the surface area of the feature. Surface areas of heated ground can be the largest features with fumaroles and primary springs generally the smallest (Figure 4). The area of steaming ground and heated ground can be highly variable with surface areas that can range over several orders of magnitude.

Temperature variations for each feature type are generally highly variable (Figure 5). The small interquartile range for geysers is expected because of the mechanism required to geyser (i.e. boiling water), however, the small range for heated ground and steaming ground is probably due to a lack of data for these feature types. Data for the other feature types is as might be expected, with primary feature types (deep source fluid) having median temperatures higher than mixed feature types (more dilute).

Median flow rates from primary and mixed springs are low (<0.5 l s^{-1}) (Figure 6). Mixed springs show a larger interquartile range. The larger range may reflect the characteristics of the geothermal system, impact of climatic conditions or groundwater levels on the mixed springs. Time series data would be required to confirm this.

Feature type, size, temperature and flow data of geothermal surface features are used as indicators to help assess the "importance" of individual features relative to the statistical properties at a national-scale. Intuitively, larger, hot, flowing primary surface features are, in general, more important compared to other features (acknowledging that this may have little or no relevance for assessing the aesthetic or cultural values of a feature). For example, a primary spring with a size of 3 m^2 would rate in the top 25% of this type of feature in New Zealand for size. This provides some national context and actual parameter values to compare features to. This data will enable developers and resource managers to be better informed about assessing the relative importance of geothermal surface features in development and/or environmental contexts.

Data used in this paper now resides in the GNS Groundwater – Geothermal Database (GGW) and forms the basis of the geothermal surface feature catalogue. This publicly available dataset can be added to, as new data and resurvey data gets collected, thus forming a "living" dataset.

Several key limitations to the data should be noted:

- All data was sourced from publicly published and available (mainly scientific) reports. We are aware there may be other public data and/or data in confidential industry reports that was not used.
- The heated ground and steaming ground feature types are under reported due to historic methods of observing this feature type. This includes locations, temperatures and sizes.
- The data are correct at the date the surface features were most recently mapped, however repeat surveys are required to obtain "modern-day" status of the features and to determine large-scale changes over time.
- There are limitations in extrapolating and reporting on trends or changes over time due to historical differences in mapping (e.g. detailed mapping vs area mapping), classifying feature types and measuring feature characteristics.

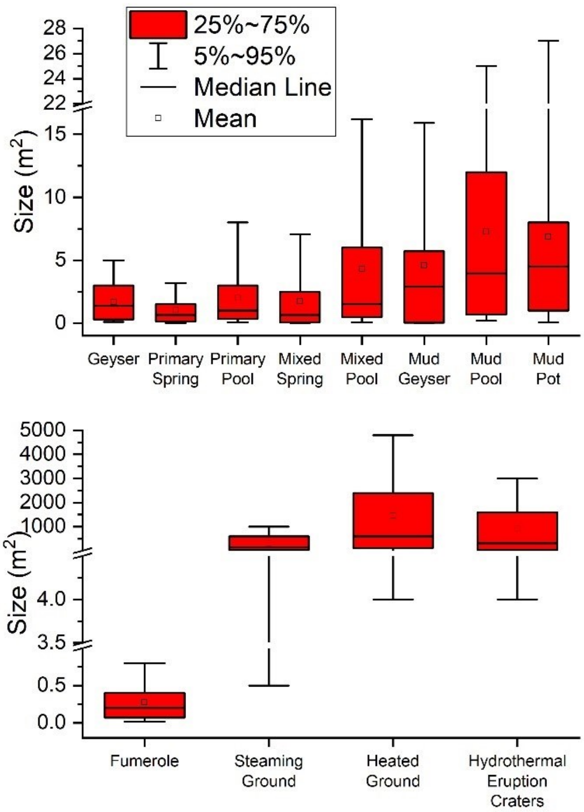

Figure 4. Statistical presentation of size for geothermal surface features.

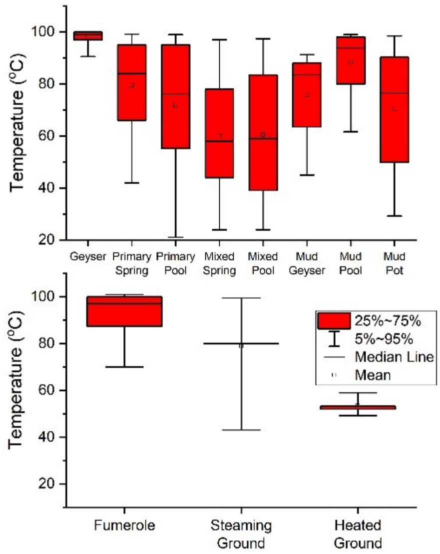

Figure 5. Statistical presentation of temperature for geothermal surface features.

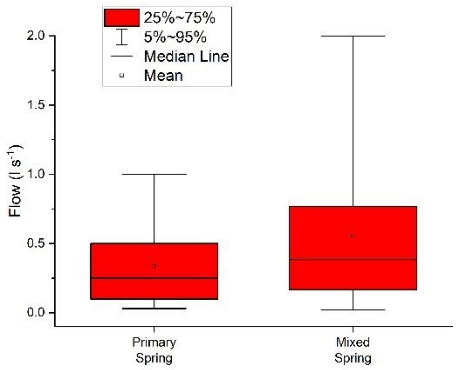

Figure 6. Statistical presentation of flow for primary and mixed springs.

4. SUMMARY

A catalogue of over 5000 geothermal surface features is compiled for New Zealand from published reports and includes both high temperature and low-temperature geothermal features from 35 geothermal fields. The catalogue uses an established method of classifying types of geothermal surface features that enables it to be searched and sorted rapidly. This data forms the basis of the New Zealand Geothermal Surface Feature Database that is readily accessible and can easily be updated with new or resurvey data.

The catalogue is a useful tool for management of geothermal systems, including state of the environment monitoring and reporting and to inform any consent applications. Feature type, size, temperature and flow are identified as key parameters that could be used to determine the importance of a geothermal surface feature relative to the national database. This can provide developers and resource managers some indication of the scientific importance of a geothermal surface feature nationally.

Additional work that could be included to improve the reliability of the catalogue include developing surface feature mapping protocols, resurveys (both ground based and aerial) and extending the catalog to include other attributes (e.g. chemistry).

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6. REFERENCES

Bay of Plenty Regional Council. 2014. Bay of Plenty Regional Policy Statement. Whakatane (NZ): Bay of Plenty Regional Council. [updated 2016 Jul 5]. (Strategic policy publication; 2013/04). https://www.boprc.govt.nz/plans-policies-and-resources/policies/operative-regional-policy-statement/

Cody, A.D., 2007. Geodiversity of geothermal fields in the Taupo Volcanic Zone. Wellington (NZ): Department of Conservation. 70 p. (DOC Research & Development Series; 281).

Hauksdóttir, S., Tulinius, H., and Kristjánsson, B. Icelandic Geothermal Database; An Online Interactive Map Interface. Proceedings World Geothermal Congress 2005 Antalya, Turkey, 24-29 April 2005.

Houghton, B.F., Lloyd, E.F., and Keam, R.F. 1980. The preservation of hydrothermal system features of scientific and other interest: A report to the Geological Society of New Zealand. Lower Hutt (NZ): New Zealand Geological Survey. 27 p.

Houghton, B.F., Lloyd, E.F., Keam, R.F., and Johnston, D.M. 1989. Inventory of New Zealand geothermal fields and features. Lower Hutt (NZ): Geological Society of New Zealand. 54 p. (Geological Society of New Zealand miscellaneous publication; 44).

Keam, R.F., Luketina, K.M., and Pipe, L.Z. 2005. Definition and listing of significant geothermal feature types in the Waikato region. In: *Proceedings of the World Geothermal Congress*; 2005 Apr 24-29; Antalya, Turkey. Reykjavik (IS): International Geothermal Association.

Muraoka, H., Gunnlaugsson, E., Song, Y., Lund, J., Bromley, C., and Rybach, L. 2010. International Database of Hydrothermal Chemistry: a Case of Task-A of Annex VIII of IEA-GIA. Proceedings World Geothermal Congress. pp 25-29.

Resource Management Act. 1991. New Zealand Government.

Reyes, A.G., Christenson, B.W., and Faure, K. 2010. Sources of solutes and heat in low-enthalpy mineral waters and their relation to tectonic setting, New Zealand. Journal of Volcanology and Geothermal Research 192. pp 117-141.

Scott, B.J. 2012. Guideline for mapping and monitoring geothermal features. Whakatane (NZ): Bay of Plenty Regional Council. 35 p. (Bay of Plenty Regional Council guideline; 2012(03)).

Scott, B.J., and Bromley, C.J. 2017. Development of Methodology to Assess Significant Geothermal Features. Lower Hutt (NZ): GNS Science. 46 p. (GNS Science consultancy report; 2017/06).

Scott, B.J., Bromley, C., Reeves, R. and Camburn, F. 2018. What makes geothermal features significant? Challenges in interpreting and applying assessment criteria. 40th New Zealand Geothermal Workshop. Taupo.

Sonney, R., and Vuataz, F. 2008. Properties of geothermal fluids in Switzerland: A new interactive database. Geothermics 37 (2008) pp 496–509.

Trumpy, E., and Manzella, A. 2017. Geothopica and the interactive analysis and visualization of the updated Italian National Geothermal Database. International Journal of Applied Earth Observation and Geoinformation 54 (2017) pp 28–37.