GEOTHERMAL MONITORING USING REMOTELY SENSED DATA AND CLOUD COMPUTING

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ABSTRACT

Geothermal features have great social and economic values, which may be impacted by the development of geothermal energy. This report provides a summary of recent environmental monitoring activities undertaken by the Waikato Regional Council utilising modern methods. Activities include mapping large areas using drones and crewed aircraft, equipped with a variety of sensors including thermal infrared, visible and near-infrared. The resulting imagery was processed using desktop and powerful cloud-based virtual machines, providing high-resolution 3D models and aerial orthophotos for areas in the TVZ (Waikite, Wairakei, Tauhara, Reporoa and Waiotapu) and northern Waikato (Gravesons Rd). Visualisation of 3D models has benefited from recent advances in immersive virtual reality (VR) technology. Ground-based surveying has utilised detailed soil CO_2 flux measurements in combination with traditional temperature probe methods on areas of steaming ground at Wairakei, Tauhara and Reporoa. These methods have provided localised estimates of heat and CO_2 flow of interest to ongoing monitoring, while addressing broader questions on the characteristics of the underlying geothermal systems.

1. INTRODUCTION

1.1 Value of geothermal areas

Waikato Regional Council regularly monitors and reports on our region's geothermal areas, the pressures they face, and how they are changing. Geothermal areas such as thermal springs, fumaroles and steaming ground are the surface expression of a geothermal system and can characterise the subsurface system when they are mapped and monitored. They also provide an indication of system response to natural variation or commercial exploitation. Mapping the locations of geothermal features, monitoring their gas emissions and heat flow can provide data for research and environmental management.

Geothermal features have great social and economic values. Their uses include tourism, bathing, heating, scientific research of gas emissions and volcanic eruptions. Māori uses of geothermal features include bathing, cooking, and ceremonial uses. Geothermal features provide valuable minerals (e.g. sulphur), and host unique ecosystems that provide a buffer to other ecosystems (from heat and toxic minerals).

In the past geothermal energy exploitation has had an adverse impact on geothermal features, in some cases water features such as geysers and hot springs have been lost to extraction of reservoir fluid. Geothermal features are relatively rare, so care must be taken to prevent damage to them.

1.2 Recent monitoring

This report provides a summary of recent environmental monitoring activities undertaken by the Waikato Regional Council utilising aerial survey techniques including i) mapping thermal areas using drones and crewed aircraft (Waikite, Wairakei, Tauhara, Reporoa and Waiotapu), ii) data processing of aerial imagery using cloud-based virtual machines (thermal infrared, visible and near-infrared), and iii) visualisation of the resulting 3D models using immersive virtual reality (VR) technology.

Ground-based surveying has been undertaken using soil CO_2 flux measurements in combination with traditional temperature probe methods on areas of steaming ground at Wairakei, Tauhara (Figure 1) and Reporoa (Figure 2). These methods have provided localised estimates of heat and CO_2 flow of interest to ongoing monitoring, while addressing broader questions on the characteristics of the underlying geothermal systems.

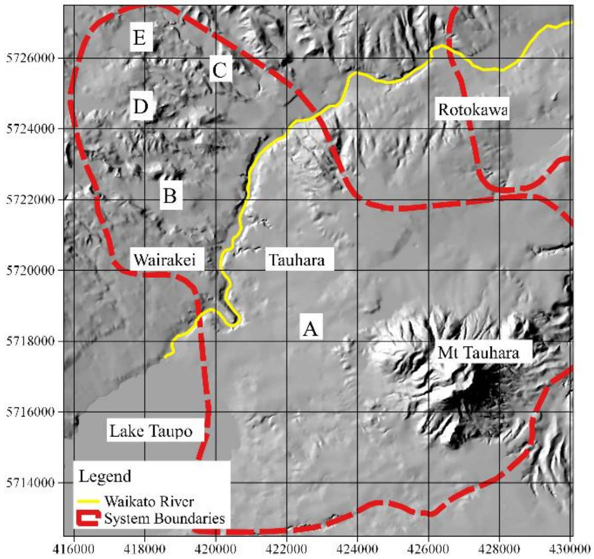

Figure 1: Wairakei-Tauhara geothermal system overlaid on a satellite digital terrain model. White boxes show ground-based (CO_2 flux and shallow temperature) survey areas at (A) Broadland Rd (Pony Club), (B) Karapiti, (C) Geyser Valley, (D) Upper Waiora Valley, (E) Hot Hill. Field boundaries are defined by shallow resistivity (Bibby *et al.*, 1995).

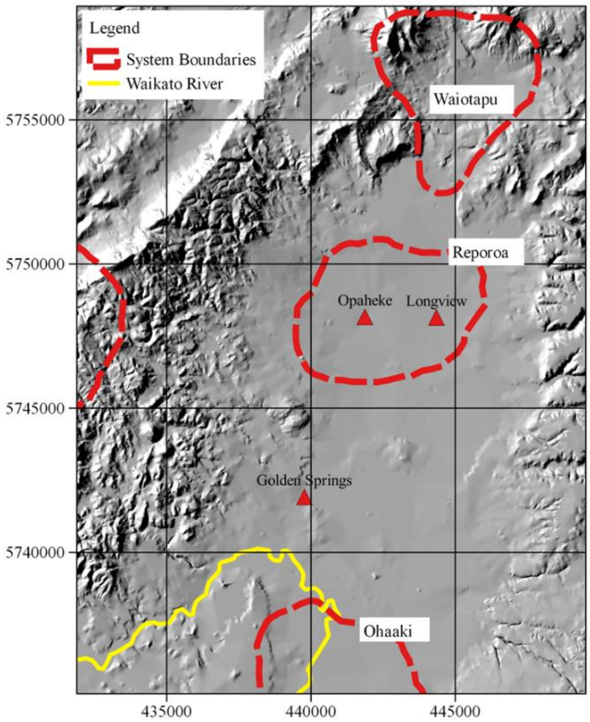

Figure 2: Reporoa geothermal system overlaid on a satellite digital terrain model. Red triangles show thermal areas. Field boundaries are defined by shallow resistivity (Bibby *et al.*, 1995). Ground-based surveying (CO_2 flux and shallow temperature) was undertaken at Opaheke. Map Datum WGS84.

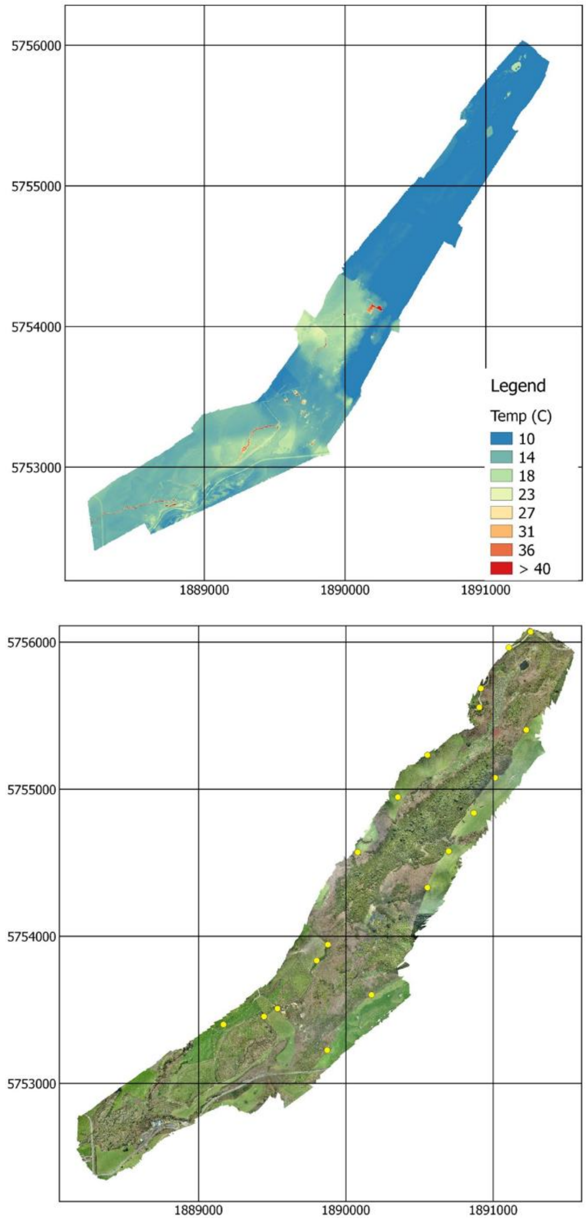

Figure 3: Waikite calibrated thermal infrared orthophoto (top) and RGB orthophoto (bottom). Yellow dots show location of ground control points. Map Datum NZGD2000.

2. MONITORING ACTIVITIES

2.1 Waikite Valley

The Waikite Valley thermal area was surveyed in October and November 2015 (Harvey et al., 2016). The survey produced a 2.2 km^2 georeferenced, temperature-calibrated thermal orthophoto, and RGB orthophoto (Figure 3). The image represents a mosaic of nearly 6000 thermal images captured by drone over a period of about 2 weeks. This was probably the first such image of a significant geothermal area ever produced by a drone equipped with a thermal camera. A similar thermal image was produced for the Gravesons Road thermal area (0.3km^2) in a single morning. Thermal features are clearly identifiable in both areas, one of the objectives of the survey.

Calibrated thermal imagery and Monte Carlo analysis provided a mean total surface heat loss of 43 ± 12 MW for thermal lakes and streams in the survey area, for the survey time period. For non-thermal imagery, the ground resolution (4cm) and horizontal position error (~10cm) are comparable to commercially produced LiDAR and aerial imagery obtained from manned aircraft. Different types of vegetation were identified (e.g. fern, grass, flax, blackberry), another objective of the survey. The position error of the thermal orthophoto was estimated by checking alignment with the georeferenced visible image and found to <1m for most of the image area. Thermal, visible and DEM imagery at Gravesons Road is of similar accuracy.

2.2 Wairakei, Tauhara and Reporoa

CO_2 flux and shallow temperature surveys were conducted on steam heated ground at Broadlands Rd, Karapiti, Geyser Valley, Upper Waiora Valley, Hot Hill and at Opaheke (Reporoa) (Figure 1 and Figure 2) as part of Mark Harvey's PhD project. Aerial RGB and TIR imagery was also collected for these areas (e.g. Figure 4 and Figure 5).

At Tauhara, a previous heat loss survey conducted during 2009-2010 estimated heat loss (56 ± 6MW) over an area of 0.5 km^2 thermal ground, including the Broadlands Rd study area (Bromley et al., 2011). Heat loss was estimated using the same method utilised in this study (i.e. Bromley et al., 2011, Method 1). Recent surveying shows a heat loss of 78 ± 7 MW for the Broadlands Rd survey area (0.37 km^2). This is significantly larger than in 2009-2010 (56 ± 6MW)(0.5 km^2

thermal ground), and suggests that heat flow has increased at Tauhara since 2009-2010. At Karapiti, calibrated thermal imagery provided a total heat flow of ~15 MW for unvegetated thermal clays (>20°C) in the survey area; it is not possible to use aerial TIR to measure heat flow from thermal soil beneath vegetation (Harvey, 2016).

A ground-based heat loss survey at Karapiti conducted during 2003-2004 (Hochstein and Bromley, 2005) estimated heat loss (138 ± 16 MW) over the same area (0.35 km^2) as surveyed in this study (Karapiti Wide Area). The earlier survey utilised the same method utilised here (Harvey, 2018; Equation 6.1). Results here provide heat loss (93 ± 4 MW) that is smaller than in 2003-2004 (138 ± 16 MW). This suggests heat flow has decreased at Karapiti since 2003-2004, continuing a downward trend since the mid 1960's (Glover and Mroczek, 2009).

A previous CO_2 flux survey at Karapiti (Werner et al., 2004) utilised the same equipment (West Systems meter), over the same area (0.35 km^2) of thermal ground as surveyed here. The 2004 survey reported total diffuse CO_2 flow (6 tons d^{-1}) similar to recent results (7.4 ± 0.6 ton d^{-1})(no confidence interval was provided for the 2004 results). Surveying at Reporoa showed very high CO_2 fluxes. In general, fluxes are highest at Reporoa and lowest at Wairakei (Figure 6).

2.3 Cloud-based processing and virtual reality

Photogrammetry processing of aerial imagery provides orthophotos, Digital Elevation Models (DEM) and 3D models, which are of interest to WRC for environmental monitoring. Processing of the Waikato Regional Aerial Photography Syndicate (WRAPS) 2017 aerial image dataset for the Karapiti area was undertaken using high-performance cloud-based virtual machines (VM's). Results showed that large aerial image datasets could be processed into very dense point clouds, quickly and economically.

Different cloud services (Microsoft Azure and Google Cloud) were investigated and compared to the typical method (standalone laptop computer) in terms of processing time and cost. Google provided the best performance; Agisoft Photoscan (processing software) frequently crashed on Microsoft Azure, which required reprocessing time. High-resolution 3D models derived from drone and WRAP's imagery were compared and showed the drone-based model texture had better contrast.

Figure 4: At Karapiti, soil CO_2 flux and shallow temperature measurement locations (white points ± 5 m) are overlaid on high-resolution drone aerial orthophoto (4cm GSD). Note areas correspond to those in Figure 5.

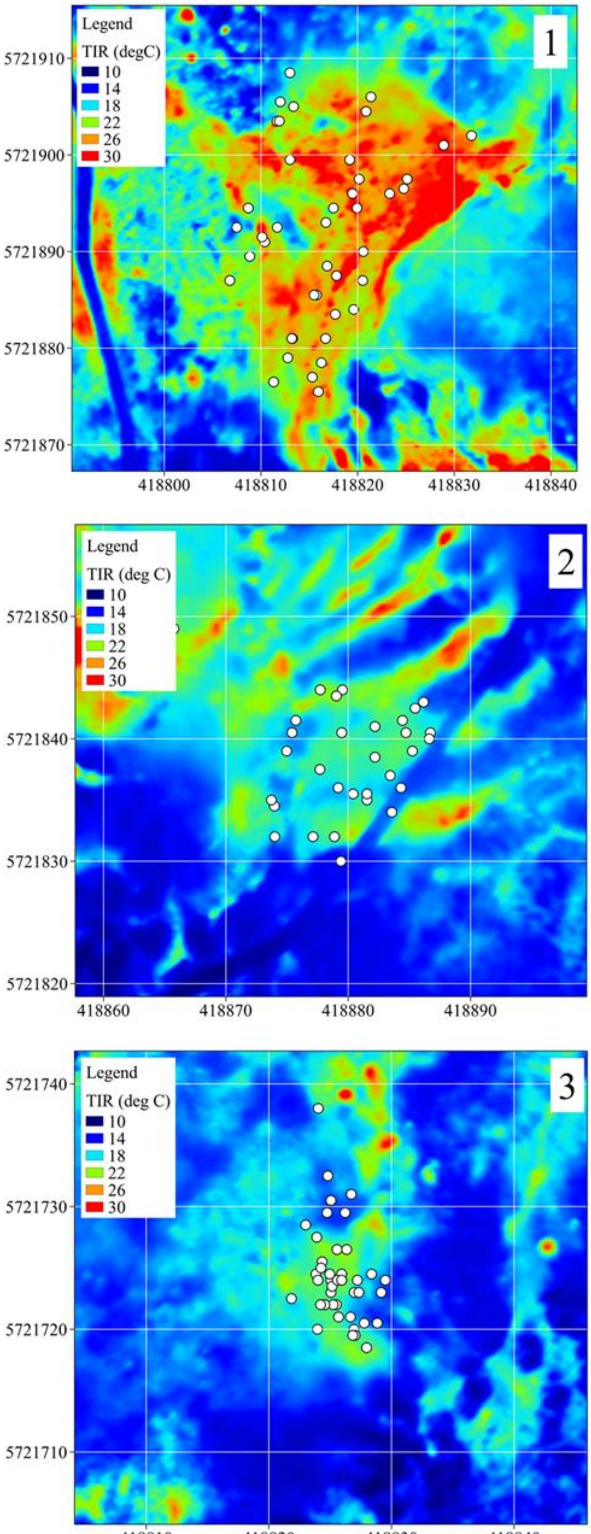

Figure 5: At Karapiti, soil CO_2 flux and shallow temperature measurement locations (white points ± 5 m) are overlaid on high-resolution drone TIR orthophoto (16cm GSD). Note areas correspond to those in Figure 4. TIR imagery was also collected at Broadlands Rd, Geyser Valley, Upper Waiora Valley, Hot Hill and at Reporoa)(Harvey et al., 2018).

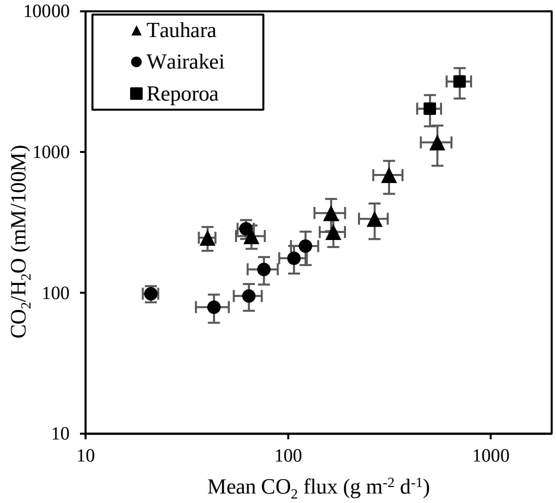

Figure 6: Cross plot showing CO_2 flux is highest at Reporoa and lowest at Wairakei.

3. DISCUSSION

3.1 Ground-based monitoring

At Tauhara, an increase in surface heat flow from steam heated ground is indicated based on surveys undertaken in 2010 and again in 2015. An increase in heat flow was previously noted for Karapiti over the period 1955 – 1965 (Allis, 1981; Glover and Mroczec, 2009), and at Reykjanes (Iceland) over the period 2004-2013 (Óladóttir and Friðriksson, 2015). At both Karapiti and Reykjanes the increase was attributed to reservoir pressure reduction and boiling due to commencement of exploitation. It is unknown if this is the case at Tauhara where exploitation commenced in 2010. Further repeat surveys would be required to verify a trend; at Reykjanes, the trend of increasing heat and CO_2 flows was identified by repeat surveying (10 surveys conducted annually).

At Karapiti, ground based surveying suggests heat flow has decreased since 2003-2004, continuing a downward trend since the mid 1960's (Glover and Mroczek, 2009). Soil diffuse CO_2 flow at Karapiti appears to have been relatively stable since 2004.

At Reporoa, previous interpretations suggested the thermal areas are supplied by fluid outflowing from Waiotapu, based on shallow-penetrating resistivity data and preliminary geochemical data (Hatherton *et al*., 1966; Healy and Hochstein, 1973). However, a connection between Reporoa and Waiotapu was later refuted on the basis of shallow (Bibby *et al*., 1994) and deep (Risk *et al*., 1994) resistivity surveying. Surveying at Reporoa showed very high CO_2 fluxes that suggests a hotter reservoir temperature than at either Wairakei or Tauhara (Harvey et al., 2017; Harvey, 2018). This also indicates Reporoa has a separate upflow from Waiotapu; a degassed outflow from Waiotapu would not be expected to have such a high gas content and/or high temperature (Harvey et al., 2017; Harvey, 2018).

3.2 Aerial monitoring

At Waikite, the mean surface heat loss 43 ± 12 MW estimate from TIR drone imagery is a probably a minimum, as a small proportion of thermal water is not visible from above (e.g.

obscured by vegetation). This value is for evaporation, conduction and radiation; it does not consider advective heat loss associated with ebullition, or advective heat loss associated with the Otamakokore stream flow (Bibby et al., 1995), which comprises nearly all surface out-flow from the survey area (43 MW, Glover et al., 1992)(46MW; Healy, 1952). Assuming a similar heat flow today, the total heat loss for the Waikite survey area averaged ~86MW during the survey period. The standard deviation of the drone-based heat flow estimate (12 MW) resulted from meteorological variations expected during the survey period (ambient air temperature, wind speed, humidity, barometric pressure).

At Karapiti, surface heat flow estimated from TIR drone imagery (15 MW) is a minimum as steam partly obscured the survey area; thermal infrared radiation is absorbed by steam. A larger heat flow value would be obtained by flying later in the day, on a colder day; relative humidity increases atmospheric steam and is usually highest in the early morning then drops rapidly after sunrise. Accordingly, optimal flight conditions for thermal survey of steaming ground are probably during periods of relatively cool, dry weather, with even cloud cover, possibly around midday. However, this remains to be tested.

3.3 Cloud-based photogrammetry processing and virtual reality

Processing of the WRAPS aerial image dataset (crewed aircraft) for Karapiti was undertaken using high-performance cloud-based virtual machines (VM's) and showed that large datasets can be processed into very dense point clouds, quickly and economically. The hourly cost of Google Compute Engine was higher but provided the best performance; Agisoft Photoscan (processing software) frequently crashed on Microsoft Azure, which required reprocessing time. *Ultra-high*-quality point clouds on both platforms are more likely to have holes/gaps than if the datasets were processed at lower quality settings. This is an expected consequence of i) the pixel matching algorithm used by the photogrammetry software, and ii) image quality.

Additional processing (i.e. beyond dense point cloud generation) may be required depending on the desired file format/end use. For example, viewing the 3D model using virtual reality currently requires further processing of the dense cloud to an OBJ file. This process was trialed for the full dataset but failed; it appears that creation of a mesh with over 300 million polygons was excessive, even for the high-spec VM's. Both Google and Microsoft VM's failed at this step.

This limitation was overcome within Agisoft Photoscan by cropping the dense cloud to an "area of interest", then continuing processing the cropped cloud (i.e. to a 3D model). The resulting smaller cropped models (~20,000 m^2) fitted conveniently within the viewing limitation on the HTC Vive virtual reality system (OBJ files viewed in the Tilt Brush application are currently limited to several million polygon faces).

Comparison of the *ultra-high* quality cropped 3D models using the HTC Vive VR system showed the drone-based model texture has better contrast than the WRAPS texture. VR technology might be used for demonstrations at meetings, conferences, education and public outreach (i.e. showcasing WRC datasets), or for health and safety briefings. More sophisticated applications (e.g. analysis of environmental change) should be possible once a time series of model data becomes available, and VR hosted software gets more sophisticated.

4. SUMMARY

This report provides a summary of recent environmental monitoring activities undertaken by the Waikato Regional Council utilising modern methods. Activities have included ground-based surveying and aerial mapping using drones and crewed aircraft.

Ground-based surveying utilised detailed soil CO_2 flux measurements in combination with traditional temperature probe methods on areas of steaming ground at Wairakei, Tauhara and Reporoa. These methods have provided localised estimates of heat and CO_2 flow of interest to ongoing monitoring, while addressing broader questions on the characteristics of the underlying geothermal systems.

Aerial imagery was processed using desktop and powerful cloud-based virtual machines, providing high-resolution 3D models and aerial orthophotos for areas in the TVZ (Waikite, Wairakei, Tauhara and Reporoa) and northern Waikato (Gravesons Rd). Use of VR in monitoring is currently limited to simple visualisation of models, but further applications (e.g. analysis of environmental change) should be possible once a time series of model data becomes available, and VR hosted software becomes more sophisticated.

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