SURFACE HEAT LOSS FROM THE WAIMANGU GEOTHERMAL VALLEY

Robert Reeves, Anya Seward, Samantha Alcaraz, Fiona Sanders, Nick MacDonald, and Thomas Brakenrig

GNS Science, Wairakei Research Centre, Private Bag 2000, Taupō, 3352, New Zealand.

r.reeves@gns.cri.nz

Keywords: *Surface heat loss,.Waimangu, aerial thermal infrared imagery, TIR, calorimetry*

ABSTRACT

The Waimangu Geothermal Valley is the youngest geothermal area in New Zealand. It was formed as a result of the 1886 Tarawera Rift eruption, and contains the world's largest hot pool (Frying Pan Lake), numerous hot springs, fumaroles and areas of steam heated ground. Surface heat loss of the Waimangu Geothermal Valley is estimated in this study, using aerial thermal infrared imagery (TIR), collected on 28 January 2017, and a terrestrial calorimetry survey combined with chloride flux measurements undertaken in March 2017.

The terrestrial heat loss survey consisted of 19 calorimeter measurements in varying landcover. The measured heat flux of these sites are scaled-up using a new land-cover map, to determine a total surface heat loss of the valley. This surface heat loss estimate is combined with a calculated evaporative heat-flow from the surfaces of the two heated lakes, Frying Pan Lake and Inferno Crater.

The total heat loss for the Waimangu Geothermal Valley is estimated to be between 326 and 353 MW using the combined TIR and chloride flux techniques, and between 294.2 and 321.2 MW using the terrestrial calorimetry and chloride flux techniques. These total surface heat loss estimates are in close agreement with each other, and historic estimates.

1. INTRODUCTION

The surface expression of geothermal systems can include geothermal surface features such as springs, geysers, hot pools, and heated ground. The amount of heat discharged from these features can be indicative of the size of the underlying geothermal resource. Accurate quantification of the surface heat loss can provide a means for long-term monitoring to help determine changes in the geothermal system over time and space.

Measuring heat flow from geothermal systems is problematic. Dangerous field conditions combined with the many types of surface expressions discharging heat that exist in geothermal systems can make direct measurements of heat flow difficult, time consuming, and nearly impossible to capture all the sources of heat. In addition, heat flow due to conduction, convection and radiation need to be considered in most New Zealand high-temperature geothermal systems to obtain an accurate estimate of heat flow. This generally results in large errors associated with any heat flow estimate.

A variety of methods have been used to measure heat flow from geothermal systems in New Zealand. This includes using chemical tracers (such as chloride mass balance, e.g., Glover 1992), conservation of mass and energy (e.g., Scott 1992a), direct measurements using calorimetry (e.g., Hochstein and Bromley 2005), remote sensing (e.g., Seward et al. 2018) and more commonly by measuring thermal gradients (e.g., Whitford and Graham 1994, Dawson and Dickinson 1970). Multiple methods may need to be used in complex geothermal environments.

1.1 Waimangu Geothermal Valley

The Waimangu Geothermal Valley, the youngest geothermal area in New Zealand, is located at the southern margin of the larger Waimangu – Rotomahana – Mt. Tarawera Geothermal Field (Figure 1). It was formed as a result of the Tarawera Rift eruption in 1886 (Simmons et al. 1993). The geothermal valley contains the world's largest hot pool (Frying Pan Lake), numerous hot springs, fumaroles and areas of steam heated ground. It is an area of scientific interest due to the recent volcanic activity and the potential for similar, or larger volcanic / hydrothermal events to occur in the region in the future.

Frying Pan Lake is located near the top of the valley, within the Echo Crater, and discharges into the Waimangu Stream that terminates at Lake Rotomahana (Figure 1). Geothermal discharge into the Waimangu Stream increases as the stream flows through the valley as geothermal waters are collected from discharging springs and streams. Inferno Crater has a cyclic water level that overflows and discharges into the Waimangu Stream (generally on a 38-day recharge cycle; Scott 1992a).

The thermal valley also contains several other craters (e.g., magmatic, phreatic-magmatic, collapse) that were formed in the 1886 eruption (Nairn 1979). These craters do not contain crater lakes and are covered in vegetation. Northeast of these craters is a rift valley containing areas of sinter deposits, steaming ground, and stunted vegetation.

1.2 Historic heat loss estimates at Waimangu

Previous terrestrial heat flow estimates from Waimangu have largely been based on the heat flow calculated from the two largest geothermal surface features – Frying Pan Lake and Inferno Crater. These two features have been used due to their large size and easy access for water temperatures and flow measurements. Based on mass and energy balances from these two features, Scott (1992b) and Nairn (1981) suggest a heat loss of 150 MW and 180 MW, respectively. Nairn (1981) also estimates another 80 MW of heat could be possible from the other geothermal features, although no measurements were made. Geochemical estimates of heat flux using only chloride-enthalpy relationships for the Waimangu Geothermal Valley range from 360 MW to 795 MW, but include discharges from the lake bed of Lake Rotomahana (Bibby et al. 1995).

This paper estimates the heat flux using a subset of methods presented in Seward et al. (2018) with geochemical methods to obtain an improved heat loss estimate for the Waimangu Geothermal Valley.

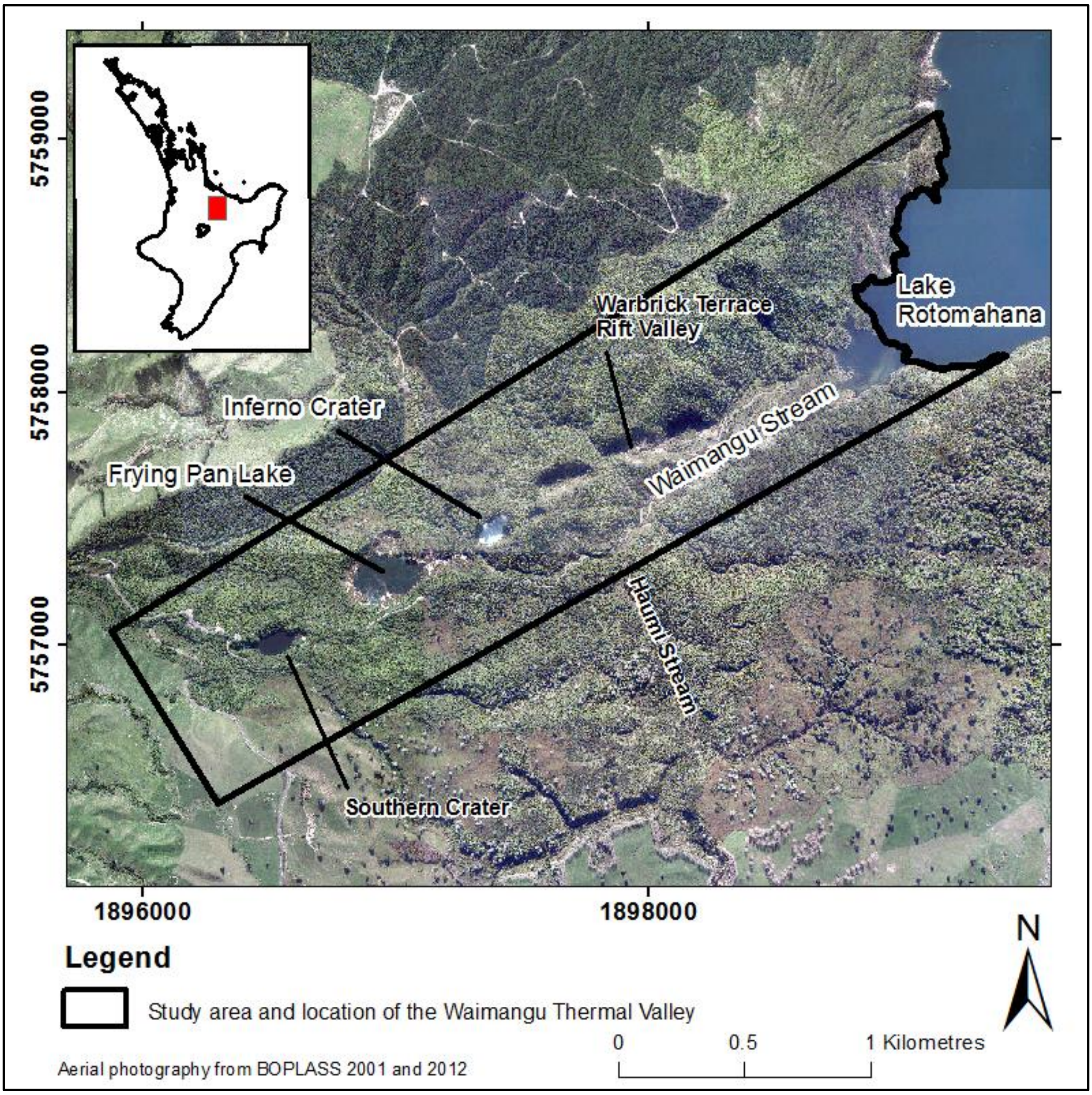

Figure 1: Waimangu Geothermal Valley study extent

2. METHODOLGY

Aerial TIR imagery, direct heat flux measurements, vegetation mapping, evaporative heat flux from water bodies and chloride balance methods are used to estimate heat loss for the study area (Figure 1).

The following sections describe the methods used to calculate a surface output using the different datasets. Note that the heat loss estimates from both the aerial TIR and calorimetry methods do not account for heat loss through mass discharge (e.g., flowing springs or streams), nor convective heat loss from fumaroles or steaming cliffs, and will therefore result in a lower than true total heat loss of the area.

2.1 Aerial TIR

Inferred surface (ground and water) temperatures derived from aerial TIR imagery collected over Waimangu on 28 January 2017 (Reeves and Macdonald 2017) is used to calculate the surface heat loss for the area shown Figure 1. An estimate for theoretical radiative, conductive and convective heat fluxes are calculated from inferred surface temperatures using the method (Method 3) described in Seward et al. (2018). Only image pixels with inferred surface temperatures greater than 18°C are used as cooler temperatures are considered to be ambient. The TIR image was collected at night between 9 pm and 11 pm, and has a ground pixel size of ~ 0.75 x 0.75 m (Figure 2).

TIR imagery provides a major advantage over other methods for mapping and estimating temperatures of geothermal surface features because of the ability to identify (temperature, spatial extent) unknown areas of heated ground or water, enabling the heat flux from these areas to be included in the total heat flux estimates. However, issues with this technique can include:

- discrepancies between the inferred ground temperature and the actual ground surface temperature caused by different emissivities of the ground surface
- steam between the ground and the TIR camera absorbs TIR, and reduces the apparent temperature of the effected pixels
- effects of atmospheric conditions during data collection, presences of clouds, changes in air temperature etc.
- ground cover impairing the TIR camera view (e.g., the TIR camera will not detect a high thermal anomaly if a tree is growing over the geothermal feature).

For the calculation of heat loss, an ambient air temperature of 12.5°C (as recorded on the BOPRC weather station located within the Waimangu Geothermal Valley), surface emissivity of 0.98 (emissivity of water; note the emissivity of vegetation can vary between 0.96 and 0.98 depending on the cover; Li et al. 2013), and a convective heat transfer coefficient of 27.7 were used.

2.1 Terrestrial heat flux

The surface heat loss determined from terrestrial measurements consists of three components, (1) surface heat flux determination using calorimetry, (2) determining an integrated surface heat loss using an updated ground cover map, and (3) determining heat loss from the water bodies.

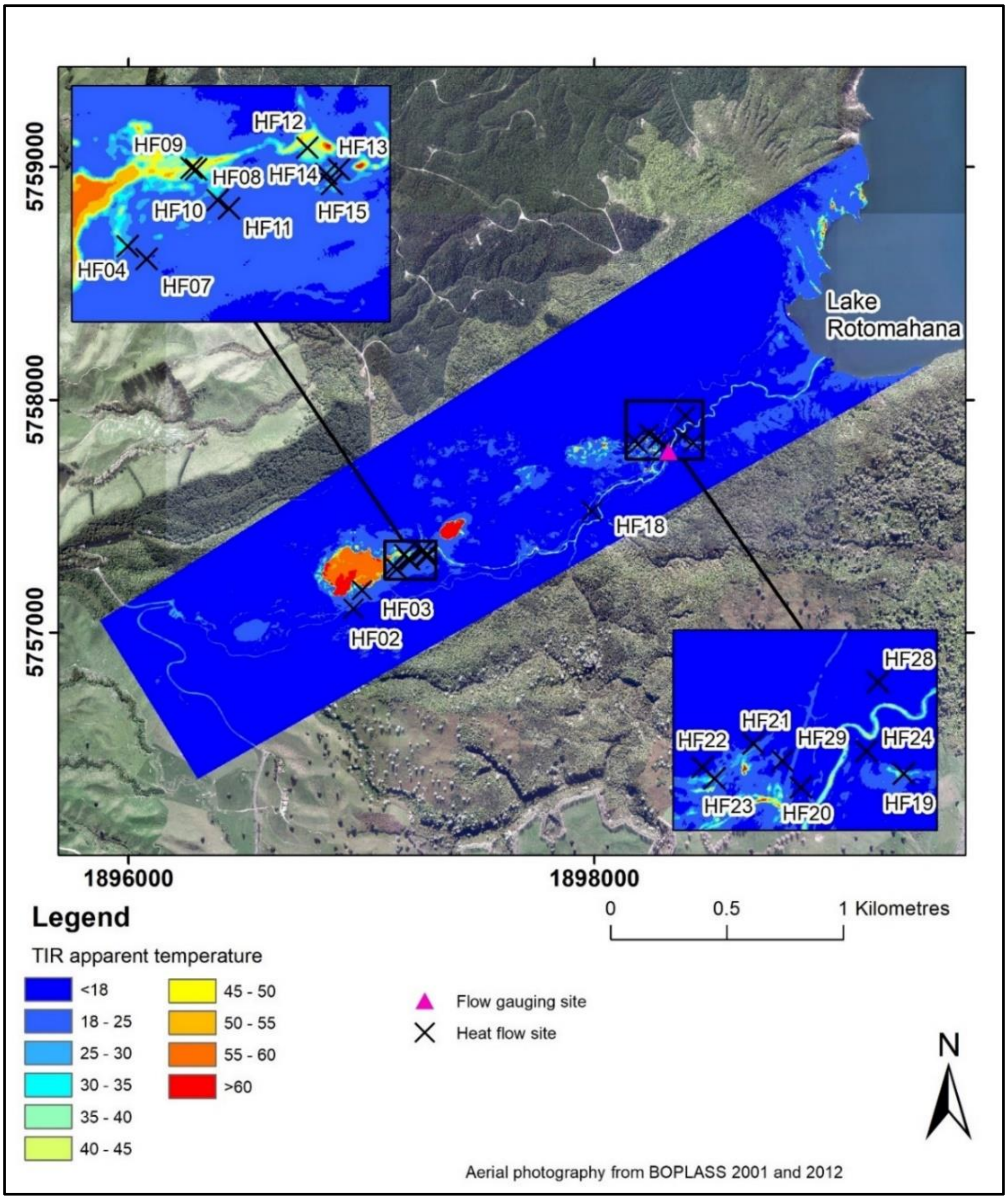

Figure 2: False colour TIR image over Waimangu Geothermal Valley collected in January 2017.

2.1.1 Calorimetry

Ground temperature-profiles and water-based calorimeter measurements were made at 19 sites in the Waimangu Geothermal Valley between March 16 and March 22, 2017. Sites covered a variety of different ground covers, vegetation types and surface temperatures. A surface heat flux is determined using a calorimeter (Hochstein and Bromley 2005). To estimate an integrated heat-loss from the ground at Waimangu (excluding heat discharged by fumarole vents) the surface heat fluxes determined by the calorimeter at each site are used as representative values for areas of similar ground cover.

2.1.2 Ground cover mapping

A ground cover map (Figure 3) with 10 ground cover categories consistent with Seward et al. (2018) is interpreted from aerial photographs (BOPLASS 2017). Some images are taken late in the day, resulting in shadows which are hard to interpret. In these situations, older images were used as references. The classification is based on the assumption that different vegetation thrives in different soil environments, and that areas of stunted growth are related to areas of warmer ground. It is possible that stunted growth of vegetation can be caused by the soil chemistry (van Manen and Reeves 2012), however, no chemical analysis of soil was done as part of this study to confirm this possibility. In general, areas of bare geothermal ground have a higher heat flow than areas with vegetation cover. Forestry and farmland grass are generally at ambient temperatures with no, or even negative heat fluxes (heat is being absorbed into the ground rather than emitted).

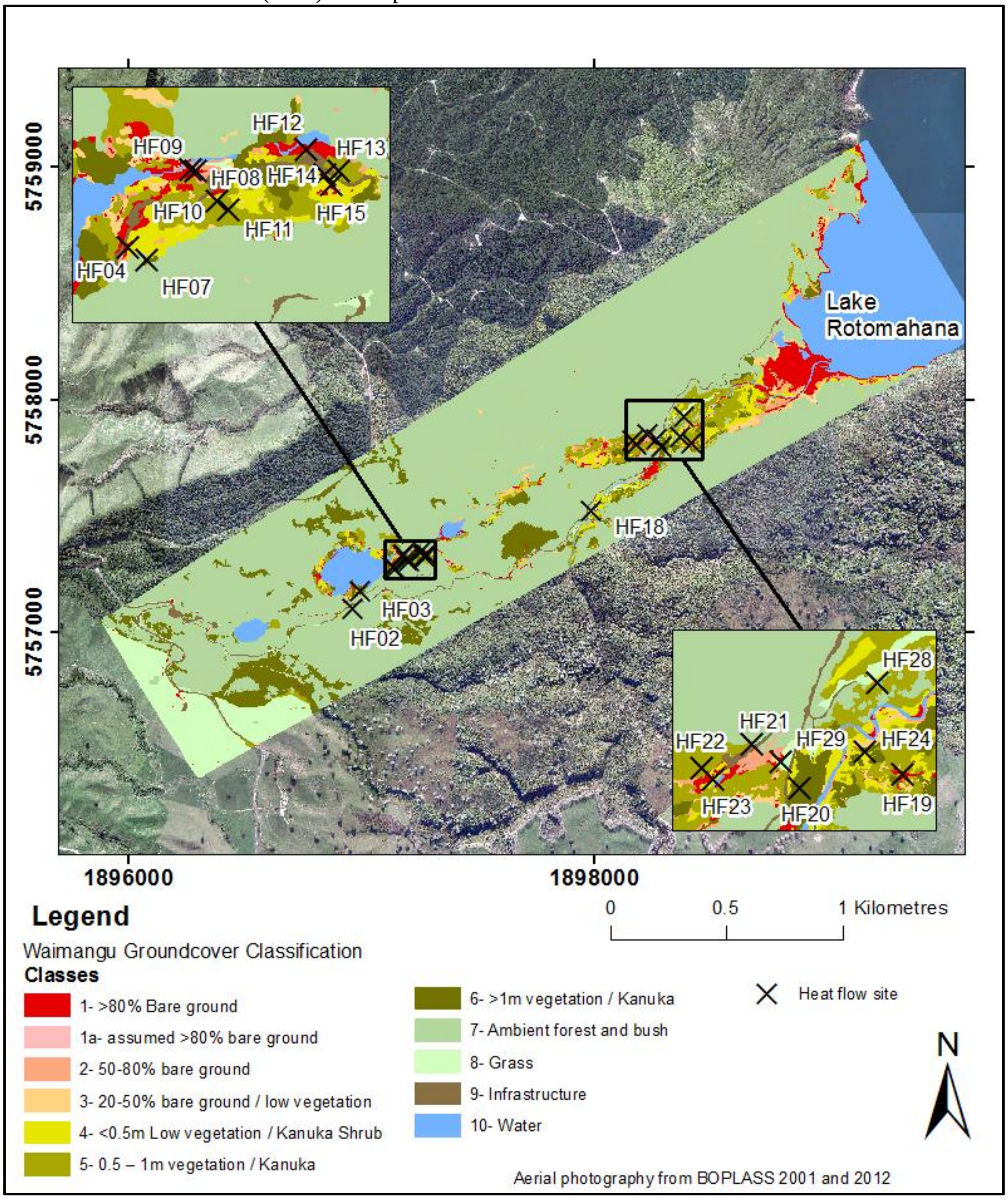

Figure 3: Ground cover Classification of Waimangu Geothermal Valley

2.1.1 Heat loss from water bodies

The evaporative heat loss from the water surfaces of Frying Pan Lake and Inferno Crater make up a large proportion of the total surface heat loss of the valley. To determine the surface heat loss of both Frying Pan and Inferno crater lakes, the method described by Adam et al. (1990) to determine the evaporative heat loss was used. This requires factors such as water temperature, surface area and windspeed to be considered.

Chloride fluxes in streams can be used to estimate geothermal heat flow (e.g., Bibby et al. 1995). This method is based on the principle that chloride ions within a geothermal fluid are conserved. Therefore, any measured chloride flux is an indication of the volume of chloride water up flowing from depth. We assume that chloride concentrations are due to geothermal inputs for the heat flux calculation.

Geothermal mass flow (chloride flux) from the valley was estimated by gauging the stream (Grid reference 1898317, 5757776; Figure 2) and collecting a water sample on January 31, 2017. The water sample was submitted to the NZ Geothermal Analytical Laboratory for analysis of chloride concentration.

To convert a chloride flux into a heat loss, the enthalpy-chloride concentration ratio of the deep geothermal water specific to the area is needed. As there are no boreholes to the deep geothermal resource in this area the chemistry of the parent water is unknown. Finlaysson and Nairn (1981) and Simmons et al. (1993) estimate the ratio to be 1.55 and 1.94 MJg^{-1}, respectively.

3. RESULTS

3.1 Aerial TIR

Over 1 million pixels (or approximately 570,000 m^2) were identified having an inferred surface temperature ≥ 18°C within the study area. Inferred surface temperatures in the valley ranged from 18°C to temperatures greater than 60°C, which results in a surface heat loss of 217 MW for the area. This value includes surface heat loss from the water surface, but not the mass flow of chloride from springs and streams.

3.2 Calorimetry & ground cover classification map

Average heat fluxes determined from calorimeter measurements for each ground-cover class are listed in Table 1. These values are upscaled using the ground cover map (Figure 3) to give a total surface heat loss through the ground for the study area of 53.6 MW.

Table 1: List of average heat fluxes used to determine a total ground surface heat loss of the study area.

Ground-cover class	Average heat flux (Wm^{-2})
1. > 80% bare ground	259.2
2. 50-80% bare ground	545.8
3. 20-50% bare ground	120.3
4. < 0.5 m low vegetation	147.6
5. 0.5 – 1 m kanuka vegetation	29.9
6. > 1m kanuka vegetation	23.7
7. Ambient forest	0
8. Grass	0
9. Infrastructure	0
10. Water	*Individually calculated.*

3.3 Heat loss from water bodies

3.3.1 Evaporative heat loss from lakes

The measured windspeed recorded in the valley was used as the representative windspeed over the lake surfaces. During the time of the TIR survey this was averaged to be 0.4 $m\ s^{-1}$. The surface area of Frying Pan Lake (Table 2) was estimated from the ground cover map, while the surface area of Inferno Crater was calculated from the measured water level recorded on the night of the survey (GeoNet 2018a). An average measured outflow temperature from Inferno Crater during the time of the TIR survey calculated from data provided by GeoNet (2018b; Table 2). The temperature at the outflow from Frying Pan Lake was used as an estimate of the average surface water temperature, although this is likely to under-estimate the heat loss as the hotter area of the lake is located at the southeastern side (opposite end to outlet; Figure 2) and will have cooled as heat is evaporated and waters are mixed before it reaches the temperature measurement site. Mongillo (1994) suggests that surface temperatures can be up to 12° hotter in the southern region of the lake than at the outlet.

An average evaporative heat flux is determined using the methods described by Adam et al. (1990) and resulted in a heat flux of 2.9 kWm^{-2} for Frying Pan Lake and a heat flux of 3.7 kWm^{-2} for Inferno Crater.

Table 2: Summary of heat loss from lakes.

Site	Surface area (m^2)	Surface temp. (°C)	Average heat flux (kWm^{-2})	Total heat loss (MW)
Frying Pan	37990	48.7	2.9	111.2
Inferno Crater	6314	51.3	3.7	23.2

3.3.2 Chloride flux

The measured flow at the stream gauging site (Figure 2) is 192 $l\ s^{-1}$ with a water temperature of 41.7 °C measured on 31 January 2017. The chloride concentration of the water sample collected during the stream gauging is 365 $mg\ l^{-1}$. This results in a chloride flux of 70 $g\ s^{-1}$ at this location.

Using these values, an estimated heat loss from discharging geothermal fluids in the study area is between 109 and 136 MW, using the enthalpy-chloride ratio of 1.55 (Finlaysson and Nairn 1981) and 1.94 MJg^{-1} (Simmons et al. (1993). It is important to note that at the time of the survey Inferno Crater was not overflowing.

4. SUMMARY AND DISCUSSION

This paper compares the heat loss derived from aerial TIR data to terrestrial measurements of calorimetry and evaporative heat loss from geothermal features in the Waimangu Geothermal Valley. The heat loss through surface discharge is determined using the chloride flux method. It should be noted that the chloride flux calculated from the Waimangu Stream also includes geothermal inputs from the Haumi Stream. These geothermal inputs are small relative to the inputs from the rest of the Waimangu Geothermal Valley.

Table 3: Summary of calculated heat loss for the Waimangu study area.

Technique	Heat loss (MW)	Discharge (MW)	Total Heat Loss (MW)
TIR	217	109-136	326 - 353
Terrestrial	188	109-136	297 - 324

Overall, there is good agreement with the heat loss calculated with the two methods, and with previous estimates. Sources of differences between the two methods could be due to:

- Evaporative heat loss for Frying Pan Lake could be underestimated because the outlet water temperature probably underestimates the average surface water temperature. Figure 2 clearly shows variations in water temperature across the lake surface.
- Calorimetry measurements were taken in March (~6 weeks after the TIR data was collected). Rainfall between the survey dates may have cooled some soil types.
- Heat loss from the surface of Southern Crater Lake is not accounted for in the terrestrial heat loss estimation. It is thought that this would only account for a small amount as the TIR images suggest a lake surface temperature of ~23°C and a surface area of 10,400m^2 (estimated from the vegetation map) which would result in an evaporative heat loss of 0.8 MW.
- Errors associated with scaling-up the calorimetry data.
- Errors associated with deriving TIR ground temperatures.

CONCLUSIONS

Heat loss determined through TIR remote sensing and terrestrial measurements were determined for the Waimangu Geothermal Valley. A total heat loss of between 294 and 353 MW is calculated for the study area. These values are likely to be underestimates as heat flux from steaming vents and fumaroles were not measured. Results between the two methods are in close agreement, with the terrestrial estimate being lower, most-likely due to a low estimate of surface temperature of Frying Pan Lake used in the evaporative heat loss calculation.

ACKNOWLEDGEMENTS

We would like to acknowledge the "New Zealand Geothermal Future" GNS Science core research funding, the Department of Conservation and Waimangu Geothermal Valley for supporting the collection and processing of the data for this project. We acknowledge the New Zealand GeoNet project and its sponsors EQC, GNS Science and LINZ, for providing the Inferno Crater data used in this study.

REFERENCES

Adam, E.E., Cosler, D.J., and Helfrich K.R.: Evaporation from heated water bodies: predicting combined forced plus free convection. *Water Resources Research.* 26(3) pp 425-435 (1990)

Bibby, H.M., Glover, R.B., Whiteford, P.C.: The Heat Output of the Waimangu, Waiotapu-Waikite and Reporoa Geothermal Systems (NZ): Do Chloride Fluxes Provide an Accurate Measure? *Proc. 17th NZ Geothermal Workshop*, 91-97 (1995)

BOPLASS. 2017. Tauranga (NZ): BOPLASS Ltd. http://www.boplass.govt.nz/

Dawson, G.B., and Dickinson, D.J.: Heat flow studies in Thermal Areas of the North Island of New Zealand, *Geothermics special issue 2*, (1970_

GeoNet 2018a. Personal communication between A. Seward and B. Scott via email 27/7//2018.

GeoNet 2018b. Personal communication between R. Reeves and B. Scott via email 10/7//2018.

Glover, R.B.,:Integrated heat and mass discharge from the Rotorua geothermal system, *Geothermics, 21 (1)* (1992)

Hochstein, M. P., Bromley, C. J.: Measurement of heat flux from steaming ground. *Geothermics* Vol 34, No. 2. Pp 131-158. (2005)

Mongillo, M.A.: Aerial Thermal Infrared mapping of the Waimnagu-Waiotapu Geothermal Region, New Zealand. *Geothermics* 23 pp 511-526 (1994)

Nairn, I. A: Rotomahana-Waimangu eruption, 1886: base surge and basalt magma. N.Z.J. Geol. Geophys., 22, pp. 363-378 (1979)

Nairn, I. A.: Geothermal Resources of the Okataina Volcanic Centre. *Geothermal Circular IAN-2.* (1981)

Reeves, R. R., Macdonald, N.: Aerial Thermal Infrared Survey of the Waimangu-Rotomahana – Mt Tarawera Geothermal Field. Lower Hutt (NZ): GNS Science. *GNS Science report; 2017/48*. 20p. (2017)

Scott, B. J.: Charateristic of cyclic activity in Frying Pan and Inferno Crater Lakes, Waimangu. *Proc. 14th NZ Geothermal Workshop*, 253-258 (1992a).

Scott, B.J.: Calorimetry and hydrothermal eruptions. Waimangu hydrothermal field, 1971-1990. *Proc. 14th NZ Geothermal Workshop*, 247-252 (1992b)

Seward, A, Ashraf, S., Reeves, R, and Bromley, C.: Improved environmental monitoring of surface geothermal features through comparisons of thermal infrared, satellite remote sensing and terrestrial calorimetry. *Geothermics* 73, pp 60-73. (2018)

Simmons, S.F., Keywoon, M., Scott, B.J., and Keam, R.L.: Irreversible change of the Rotomanhana-Waimangu hydrothermal system (New Zealand) as a consequence of a volcanic eruptions, *Geology*, 21, pp 643-646 (1993)

Van Manen, S., and Reeves, R., An Assessment of changes in *Kunzea ericoides* var. *microflora* and other hydrothermal vegetation at the Wairakei-Tauhara Geothermal Field, New Zealand. *Environmental Mangaement* 50 (4) pp 766-786 (2012)

Whitford, P.C. and Graham, D.J.: Conductive heat flow through the sediments in Lake Rotomahana, New Zealand, *Geothermics, 23(5/6)*, pp 527-538 (1994)