SURFACE HEAT LOSS ASSESSMENT OF ROTORUA GEOTHERMAL FIELD

Anya Seward[1], Rob Reeves[1], Penny Doorman[2], Fiona Sanders[1], Sabine Lor[3], Nick Macdonald[1], Thomas Brakenrig[1] and Duncan Graham[1]

[1]GNS Science, Wairakei Research Centre, Private Bag 2000, Taupo 3352, New Zealand

[2]Bay of Plenty Regional Council, P.O. Box 364, Whakatane 3158, New Zealand

[3]Grenoble Institute of Technology, ENSE3, 46 avenue Felix Viallet, F38031 Grenoble, France

a.seward@gns.cri.nz

Keywords: *Rotorua, Geothermal Surface features, heat loss, heat flux*

ABSTRACT

Rotorua City is built around the active Rotorua Geothermal Field (RGF) which is valued for its areas of surface activity utilised for cooking, bathing, heating, and tourism. Understanding and monitoring changes in this dynamic geothermal system is crucial in allowing the resource to be used sustainably, while protecting the natural geothermal surface features. Changes in activity of geothermal features over time can indicate changes that may be occurring within the geothermal reservoir due to either natural or anthropogenic causes. Estimating heat loss from a geothermal field provides an indication of thermal activity present in the geothermal system at depth. We present a surface heat loss assessment of the Rotorua geothermal system and compare the results to earlier heat loss surveys, to assess changes in surface heat output. Flow rates, water temperatures and chemistries of major flowing springs and streams were measured, as well as water temperatures and surface areas of large geothermal pools. Calorimetry and ground temperature profiles were also collected from areas of ambient, heated and steaming ground. Evaporative heat loss is a key component of the total heat loss when there is a large surface area of water associated with naturally occurring geothermally heated springs and pools (as occurs in Rotorua). Calculated evaporative surface heat loss from the surveyed geothermal pools is estimated to be 248 MW. Total heat loss (evaporative, discharging flow, convective and conductive heat losses) for the areas surveyed is estimated to be 299 MW. This encompasses approximately 80% of the thermal areas in the RGF.

1.THE ROTORUA GEOTHERMAL FIELD

The Rotorua Geothermal Field (RGF) is one of 25 major geothermal systems that lie within the Taupo Volcanic Zone (TVZ), North Island (Wilson and Rowland, 2016). It covers an area of approximately 18-28 km^2 and is considered to be one of the larger geothermal systems within the TVZ (Bibby et al., 1995). The city of Rotorua is located on the southern margin of the field, with over 1500 mapped geothermal surface features (Reeves and Rae, 2016). Surface features include hot springs, hot pools, steaming and heated ground, fumaroles, geysers and mud pools. They are largely confined to three key areas within the city: (1) South: Whakarewarewa and Arikikapakapa, (2) North: Kuirau Park and Ohinemutu, and (3) Northeast: Government gardens, Sulphur Bay and Ngapuna (Figure 1). These areas are fed through relatively shallow geothermal aquifers at depths of less than 200 m beneath the ground surface. This shallow resource and associated surface features have been an attraction to tourists, and utilised by iwi and residents, since the region was populated. Over-exploitation of the resources in the 1960's and 1970's however, resulted in a decline in activity of many surface features, with several of the active geysers and hot springs in the area stopping flowing completely (Cody and Lumb 1992).

In the 1980's a monitoring program was established, which systematically monitored key geothermal surface features and well water levels (Cody and Lumb 1992). Results showed a decrease in aquifer pressure, a change in frequency of eruptions of Pohutu geyser, and a decrease in spring activity. This led to a government-enforced management regime being introduced in 1987. This included a bore closure programme which closed bores within 1.5 km of Pohutu geyser (Figure 1), and a requirement for reinjection of geothermal fluid, where previously much fluid has been discharged to shallow soakage or surface water. These changes contributed to a decrease in exploitation by ~60% (Allis and Lumb 1992).

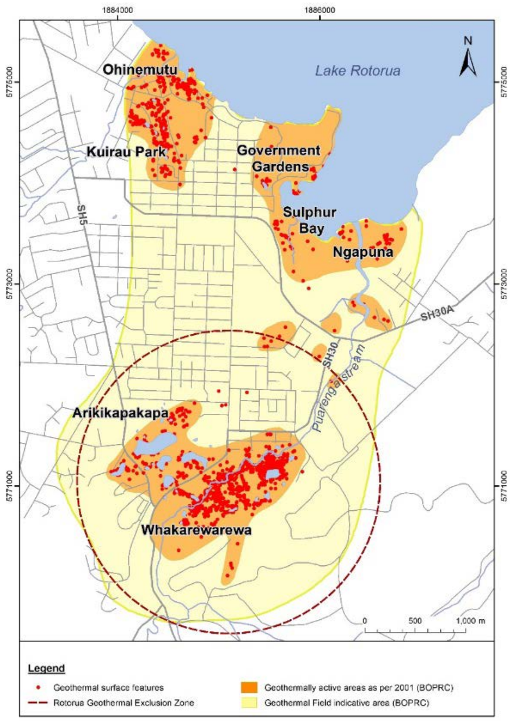

Figure 1: Regions of geothermal surface activity in the Rotorua Geothermal Field (RGF). Red dashed circle shows the boundary of the geothermal use exclusion zone.

The RGF was the subject of numerous studies between 1980 and 1990, and again in the early 2000's (see Scott et al 2016). Aquifer pressure was seen to be increasing by 1991 and some surface features showed signs of returning activity. The system now seems to have stabilized, with substantial recovery of some surface features, but variable results in other parts of the system.

A geothermal management plan for the RGF is currently in place under the authority of the Bay of Plenty Regional Council (BOPRC). To inform sustainable management of the system, the Council has a state of the environment monitoring programme including groundwater and surface feature monitoring, and also carries out other research in collaboration with Crown Research agencies to assess the state of the system. This paper outlines the first field-scale surface heat loss assessment of the RGF since the early 1990's, undertaken as part of the BOPRC monitoring of the RGF.

2. SURFACE HEAT LOSS ASSESSMENTS

Estimating heat loss from a geothermal field provides an indication of thermal activity present in the geothermal system at depth. Geothermal surface features (such as hot springs, pools and heated ground) occur where geothermal fluids are discharged at the ground surface. Heat loss monitoring can reveal when and where large-scale changes in the thermal regime (aquifer pressure and temperature) are occurring within a geothermal system and can provide useful inputs into calibrating numerical models of geothermal systems and therefore improved forecasting of the effects of energy use through scenario modelling (e.g., Ratouis et al. 2016).

Glover (1992) assessed the heat discharged from the RGF by measuring flow rates, temperatures and pH values for streams flowing into and out of Lake Rotorua. Water samples were also collected and analysed for Li, Na, K, Mg, Ca, SO_4 and Cl. A heat output was estimated using the method of Ellis and Wilson (1955), where it is assumed that the measured Cl originated from one uniform deep geothermal source, and that the total thermal output can be obtained by multiplying the measured Cl flux by the enthalpy of the deep geothermal parent water (assumed to be 0.87 MJ/g). This resulted in a total heat loss of 470 MW for the RGF. Of this, only 40% (197 ±10 MW) is accounted for from surface discharge, suggesting that a large proportion of the heat output seeps into Lake Rotorua through subsurface vents. The heat loss value calculated by Glover (1992), does not consider the proportion of heat that is lost to the atmosphere through steam discharges and evaporation.

Additional investigations into surface heat loss from the RGF focused on Whakarewarewa geothermal area. Simpson (1985), calculated heat fluxes from individual springs and pools in the area, as well as numerous ground temperature sites. 279 geothermal surface features were surveyed during 1967-69, with a follow up survey in 1984-85 of over 530 features. Simpson (1985) used the methods outlined by Dawson (1964) to estimate the surface heat loss from geothermal surface features in the Whakarewarewa geothermal area and found a significant (31%) decrease in surface heat output between 1967 and 1985.

This paper presents the results of the first systematic evaluation of the surface heat loss from the RGF since the bore closure program in the mid 1980's. Surface features located in Whakarewarewa, Arikikapakapa, Kuirau Park, and Sulphur Bay / Government Gardens were surveyed (Figure 2). Unfortunately, features located in Ngapuna and Ohinemutu were not able to be accessed during this survey, therefore we estimate that the results calculated in this paper represent approximately 80% of the total surface heat output from geothermal surface features of the RGF. Figure 2 shows the location boundaries of the geothermal areas. The boundary between Sulphur Bay and Ngapuna is given by the Puarenga stream. No sites located to the east of the stream were surveyed. Similarly, the boundary between Kuirau Park and Ohinemutu is given by Lake Road. No sites north of Lake Road were surveyed during this project.

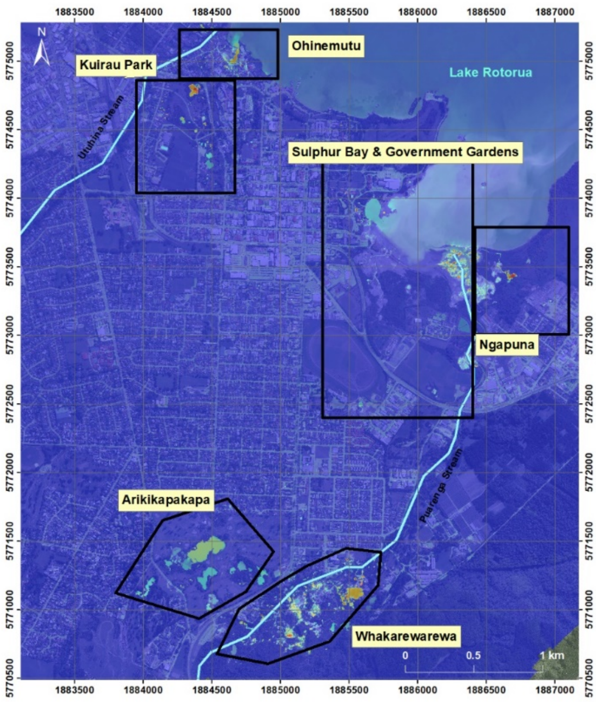

Figure 2: Boundaries of survey areas, overlaying a thermal infrared image collected by Reeves et al. (2014). Red, orange and yellow colours in the TIR image indicate areas of heated ground/water with generally a geothermal origin. Blue colours indicate ambient surface temperature conditions.

3. SURVEY

Four key data sets were collected during the field campaign. They consisted of:

- Surface temperatures, areas and outflow rates of geothermal **pools.**
- Flow rates, temperatures and water quality (chloride and sulphate concentrations) of geothermal flowing **springs.**
- Water temperature, flow rate and water quality (chloride and sulphate concentrations) of **streams and waterways.**
- Ground temperature-depth profiles to a maximum depth of 1 m, and terrestrial calorimetry (**surface heat flow**).

Geothermal pools with the largest thermal signatures, as detected by the 2014 TIR survey (Reeves et al. 2014) were targeted as priority sites for investigation. Surface water temperatures were measured at < 2 cm below the pool surface, while surface areas were estimated on site, and later compared to recent aerial imagery for more accurate area estimations. Flows from outflow channels were also measured.

Geothermal springs were surveyed for water temperature, flow rate and water chemistry. Water samples were collected and analysed at the New Zealand Geothermal Analytical Laboratory (NZGAL) for chloride (Cl) and sulphate ($S0_4$) concentrations. Water temperatures were measured mid-flow and close to source of the spring, while flow rates were measured either at source or at a suitable location with a clear flow channel, close to the source. Water temperature, flow rate and water chemistry were also collected from the Puarenga and Tawera Streams, as these represent outflow from the Whakarewarewa and Kuirau park areas, respectively.

Near-surface ground temperature measurements were also collected sporadically across the geothermal areas. Ground temperatures were measured at 5, 10, 15, 20, 25, 50 and 100 cm depth. Calorimetry measurements were also undertaken at selected sites with high temperature or steaming ground.

Field data was collected between February and April 2018. A total of 116 water features were surveyed. Thirty-four of these sites were also sampled for chloride and sulphate concentrations which enabled chloride balances to be estimated. 131 ground temperature profiles were measured, and six calorimeter sites were surveyed. Additionally, the Puarenga Stream was gauged at five locations as it flowed through Whakarewarewa. Water samples were collected at the gauging sites. Data collection was limited to days where there was little or no rain, as large amounts of meteoric water can cool water surfaces of pools, dilute spring water chemistry and dampen near surface soil temperatures. Care was taken to survey water features as close together in time as possible to minimise the effects of changes in atmospheric pressure and weather patterns on the heat output of the geothermal surface features. Figure 3 shows the geothermal water feature sites (Figure 3a) and ground temperature sites (Figure 3b) surveyed during this campaign.

4. ANALYSIS

4.1 Determining heat flow from heated pools

Heat is predominately lost from the surface of geothermal pools through evaporative processes, although radiation and conduction cannot be ignored. Equations described by Dawson (1964) to determine heat loss from the surface of geothermal pools consider the evaporative, radiated and conductive components of heat transfer and have been converted into SI units by Fridriksson et al. (2006).

Historically, the methods of Dawson (1964) have been used to calculate surface heat loss from the pool surface in Rotorua (Cody and Simpson 1985; Simpson 1985). In this study we have calculated the surface heat loss using the methods described in Fridriksson et al. (2006).

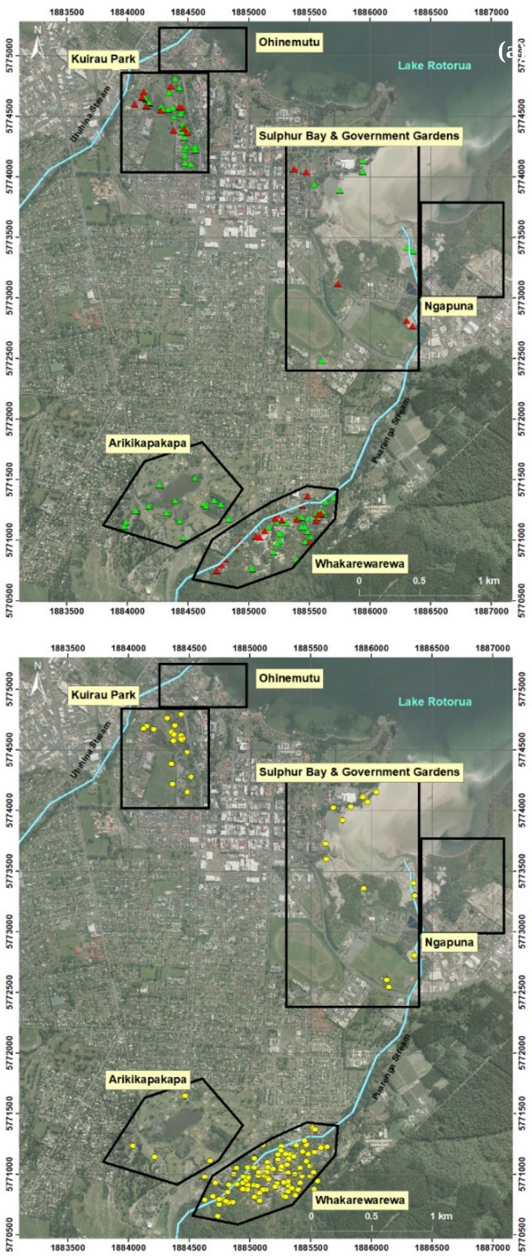

Figure 3: Locations of (a) water feature and (b) soil temperature measurement sites surveyed during the 2018 heat flow survey. Red triangles show the locations of the "spring" sites where water samples were taken.

4.2 Determining heat flow from flowing springs and streams

The measurement of the heat content of a stream into which geothermal features discharge has been used historically to determine heat flow (Glover 1992). This method assumes to capture the total heat loss from a geothermal area through flowing springs and is thought to be more accurate than measuring the total outflow of individual springs in a geothermal area (Miotti et al, 2010). This method, however, does not capture the heat loss through evaporation. We have measured temperatures, flow rates and chloride / sulphate concentrations in two key streams, which capture the outflow from Kuirau Park and the Whakarewarewa thermal area. Chloride and sulphate fluxes are calculated by multiplying the concentrations (mgL^{-1}) by the measured flow rate (Ls^{-1}) at the survey site. The heat flow is calculated by multiplying the measured flow rate by the enthalpy of the stream water at a measured temperature. The heat flow into the Puarenga Stream from the Whakarewarewa geothermal area is estimated from the water composition, temperature and flow data collected both upstream and downstream of Whakarewarewa geothermal area, as the stream contains a large meteoric component. Identified changes in temperature, chloride and sulphate concentrations are assumed to be due to the addition of geothermal waters as the stream collected the geothermal inflow from Whakarewarewa.

An assessment of spring discharge was also undertaken to determine heat flow from flowing geothermal surface features. The heat is transferred in flowing features both by direct discharge and by evaporation. Heat loss by direct discharge is calculated by multiplying the mass flow (kgs^{-1}) by the enthalpy of the water ($KJkg^{-1}$) (Sorey and Colvard 1994). The evaporative component is estimated following Fridriksson et al. (2006) as described for the pools.

4.3 Determining heat flow from heated ground

Areas of heated ground are common in geothermally active regions. Most surface expressions are associated with diffuse discharges of ground vapour consisting of conductive heat flux as well as convective steam flows (Hochstein and Bromley 2005). The convective heat flux accounts for a large percentage of the total heat flux from warm ground, in some cases up to 50% (Bromley et al. 2011).

There are several methods used to determine heat flow through heated ground in New Zealand. These include methods described by Dawson (1964), and Hochstein and Bromley (2005). Here we used the methods described by Hochstein and Bromley (2005) in which the thermal gradient of the top 1 m of the ground is used to determine the heat flux.

For areas where heat transfer is predominately conductive (e.g. ambient ground), the 1 m ground temperature gradient is multiplied by the thermal conductivity of the soil to determine the conductive heat flux. However, in areas of heated and/or steaming ground, the thermal gradient will not be linear, due to the convection of steam in the near surface. An extrapolation technique is used to determine the depth to boiling point (Hochstein and Bromley 2005). The boiling point depth is then used to infer surface heat loss using an empirical equation derived between heat loss determined from calorimetry and the boiling point depth (Seward et al 2018b). It is assumed that conditions in Rotorua are similar to those in the Wairakei and Tauhara Geothermal Fields, where 85 heat flux measurements were made and used to determine the empirical relationship defined in Seward et al (2018b).

Heat flux at six locations was also measured directly using a calorimeter (Hochstein and Bromley 2005; Seward et al 2018b). The calorimeter allows direct measurement of conductive and convective heat flux, by heating a known volume of water by either direct contact with the heated ground, or by capturing the convective component only by elevating the calorimeter 2 cm off the ground's surface. A linear rate of temperature increase is caused by steady ground heat transfer over a short time-period (typically 5 minutes). From these observations the heat flux can be calculated using equations outlined by (Hochstein and Bromley 2005). These measurements also served as a check to whether the empirical relationship between heat flux and boiling point depth is applicable to Rotorua.

The total surface heat loss for Rotorua is estimated through the use of the thermal infrared images collected by Reeves et al. (2014; Figure 2). Surface temperatures were categorised into bands of 2°C. An average of the calculated heat fluxes within the banded areas were calculated and multiplied over the total land area associated with the temperature band to give a total heat loss value for the area. This method differs to the methods used in previous surveys, where the area was estimated by contouring the measurements sites.

5. RESULTS AND DISCUSSION

A total surface heat loss for the RGF is calculated from the area surveyed during the 2018 survey to be ~299 MW. Table 1 summarises the heat loss from each geothermal area. It is important to note that the heat loss through discharging springs at Sulphur Bay is unaccounted for due to unsafe access. Arikikapakapa has no measurable spring discharges, with most heat loss derived from geothermal activity associated with large pools and mud features. This is similar to observations at Kuirau Park, where approximately 99% of the measured heat loss results from evaporative and radiated heat loss from pool surfaces.

Table 1 Summary of results. Heat flows are given MW.

Area	Total (MW)
Whakarewarewa	141
Sulphur Bay	12.8
Arikikapakapa	72
Kuirau Park	73.4
Summed	**299.2**

Whakarewarewa:

Whakarewarewa geothermal area is located on the southern margin of Rotorua, and contains numerous geothermal features including hot pools, chloride springs, steaming ground and several erupting geysers, including Pohutu Geyser (Figure 4). Due to time constraints only select features were survey during this project. Surveyed features were targeted using an aerial thermal infrared image (Reeves et al 2014) to identify the features with the largest thermal signature, e.g high surface temperatures and/or large surface areas. These features emit the highest amount of surface heat and are estimated to represent >90% of the heat output within Whakarewarewa. In total, 19 springs, 39 pools, 90 ground temperatures and 4 calorimeters measurements were made in Whakarewarewa.

Water samples were collected for analysis in the 19 springs. The chloride concentration of these springs ranged between 450 and 627 mgL^{-1}, with the exception of the THC Blowout (Figure 4), which has a chloride content of 1036 mgL^{-1} and a very small sulphate content (62 mgL^{-1}). The THC Blowout feature is a man-made feature that was formed when a bore blew out in 1987. This feature discharges deeper geothermal fluids to the surface with very little mixing with groundwater systems.

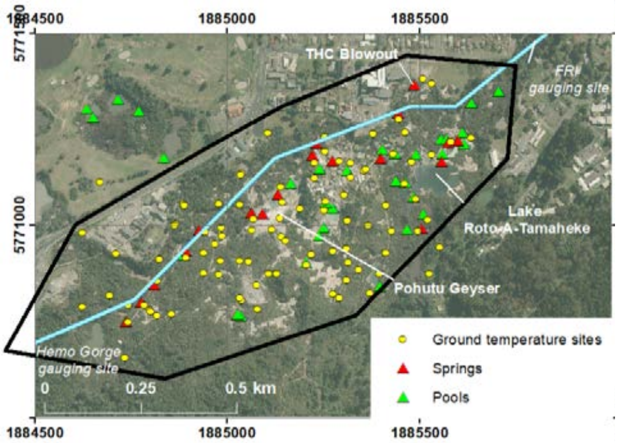

Figure 4: Survey sites within the Whakarewarewa geothermal area.

Whakarewarewa contains a large number of geothermally fed pools, with the largest one being Roto-a-Tamaheke. Surface temperatures of the pools range from near ambient to 100°C. Table 2 lists the total heat loss from the pools (including spring catchments) in Whakarewarewa. Discharge from the springs, pools and geothermal seeps in Whakarewarewa flow into the Paurenga Stream. The Puarenga Stream has an average flow rate of water between 1860 and 1940 ls^{-1} as it flows between Hemo Gorge and FRI gauging site. Water temperature increases of 5.6°C and 3.7°C were measured between gauging sites Hemo Gorge and FRI gauging site on 20 March 2018 and 19 April 2018, respectively. A total heat loss discharged from Whakarewarewa into the Puarenga Stream of between 30 and 37 MW was calculated from the observations obtained on these days. The average chloride and sulphate mass fluxes show that there is a significant increase in geothermal water downstream of the geothermal area confirming that a large proportion of the measured temperature increase in the Puarenga Stream is due to the input from heated geothermal water.

Four calorimeter measurements and 90 ground temperature profiles were made within Whakarewarewa during this survey. All of the calorimeter sites were located on bare geothermally altered ground. Three of the four sites showed surface heat fluxes of between 630 and 750 Wm^{-2}. The other one measured a comparatively low surface heat flux (55 Wm^{-2}) using the calorimeter, but higher when measuring the ground temperature profile (194 Wm^{-2}). The ground at this site had a surface temperature of 28 °C, but very little moisture, suggesting that there was a thin non-permeable layer in the shallow subsurface preventing the steam from reaching the surface. Ground temperature profiles were located in a variety of settings, ranging from ambient sites to actively steaming areas (where safe to access). Calculated surface heat fluxes reached as high as 1080 Wm^{-2} (Figure 5). The total heat flow through the ground at Whakarewarewa of 9.81 MW (Seward et al 2018a). Total heat loss for all the Whakarewarewa feature types listed is shown in Table 2.

Table 2: Measured heat flow from Whakarewarewa geothermal area (0.7 km²).

	Measured Heat flow
Surface heat flow from pools	97.7 MW
Surface discharge from measured springs	12.7 kW
Heat flow into Puaranga stream	37 MW (20 March 2018) / 30 MW (19 April 2018)
Estimated total surface heat flow through ground	9.8 MW
Total (using an averaged Puarenga heat flow of 33.5 MW)	**141 MW**

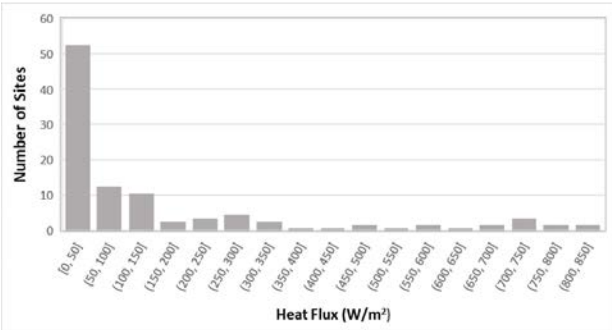

Figure 5: Histogram of ground heat fluxes measured in Whakarewarewa.

Arikikapakapa

The Arikikapakapa geothermal area is next to the Whakarewarewa geothermal area in the south of the RGF. It is situated primarily within the grounds of the Arikikapakapa golf course. It contains mixed pools, with a few mud pools and patches of heated ground. 12 pools and four ground temperatures were surveyed during this project (Figure 6). Pools ranged in surface temperature from 22.3 °C to 73.7 °C, while ground temperatures were predominately ambient, except for one (A5), which has a calculated heat flux of 366 Wm^{-2}. A total surface heat flux for Arikikapakapa is listed in Table 3.

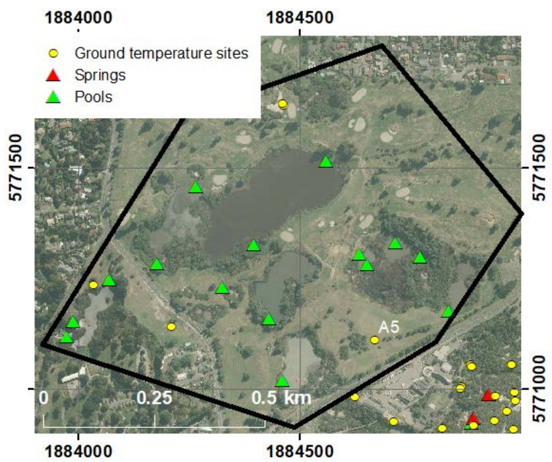

Figure 6: Survey sites in Arikikapakapa geothermal area.

Table 3: Measured heat flow from Arikikapakapa geothermal area (0.6 km²).

Proceedings 42nd New Zealand Geothermal Workshop
24-26 November 2020
Waitangi, New Zealand
ISSN 2703-4275

	Measured Heat flow
Surface heat flow from pools	71.5 MW
Surface discharge from measured springs	N/A
Estimated total surface heat flow through ground	0.5 MW
Total	**72 MW**

Sulphur Bay

Sulphur Bay is located on the southern margins of Lake Rotorua and includes both the geothermal areas of Sulphur Bay and Government Gardens (Figure 7). The Sulphur Bay geothermal area is next to the Ngapuna geothermal area, which was not surveyed during this project. The surface geothermal features of Sulphur Bay include hot pools, springs and seeps along the banks of Lake Rotorua, and the Puarenga Stream outflow. There is also a large hydrogen sulphide gas output in the area. Surveyed features (Figure 7) were targeted using the aerial thermal infrared image (Reeves et al. 2014, Figure 2) with a high consideration for the safety of the field teams.

Water samples were collected in five springs for analysis. The water temperatures of these springs ranged between 67 °C and 95 °C, with chloride concentrations ranging between 540 and 1851 mgL^{-1}. Two springs with chloride concentrations >1000 mgL^{-1} are located along the banks of the Puarenga Stream, while the other three springs (ranging between 540 and 660 mgL^{-1}) are located in Government Gardens and Sulphur Bay. Not flow rates could be measured, due to low or non-existing flow at the time of the survey.

Thirteen pools were surveyed. Pool temperatures ranged from 28 °C to 94 °C. Several pools in the Sulphur Bay area were unsafe to access, so the surface heat flow estimated for this area is a minimum.

Two calorimeter measurements were collected in areas of bare and visible steaming ground. One of these sites (R1, Figure 7) was ambient. The other site (R2, Figure 7), was located in Sulphur Bay, in an area of actively steaming ground. A surface heat flux of 410 Wm^{-2} was determined and is thought to be representative of the majority of the Sulphur Bay area. Fourteen ground temperature profiles were collected in the area, ranging from ambient sites to sites with heat fluxes of > 1000 Wm^{-2}. A total surface heat flow from the ground in the area was calculated using the TIR image collected in 2014 (Reeves et al. 2014) to estimate land area of "like" ground. Table 4 lists the total measured heat flow from the different features in the Sulphur Bay / Government Gardens area. As previously mentioned this will be a minimum estimation of heat loss.

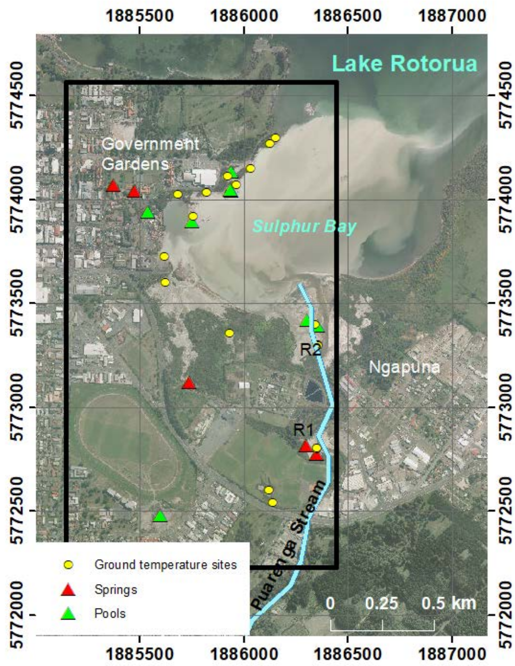

Figure 7: Survey sites in Sulphur Bay

Table 4: Measured heat flow from Sulphur Bay geothermal area (~ 3.1 km^2).

	Measured Heat flow
Surface heat flow from pools	6.2 MW
Surface discharge from measured springs	Not accounted for
Estimated total surface heat flow through ground	6.6 MW
Total	**12.8 MW**

Kuirau Park

Kuirau Park is located south of the geothermal area of Ohinemutu (Figure 3). It covers a ground area of ~590 m^2 and encompasses numerous hot pools and springs. Measurements of 40 geothermal pools, 11 geothermal springs, 17 ground temperature profiles, one calorimeter and a temperature and flow rate measurement at the Tarewa Stream (Kuirau Park outflow) were made in the park (Figure 8).

Water analysis of the springs in the Kuirau Park area showed chloride concentrations ranging from 280 mgL^{-1} to 396 mgL^{-1}, suggesting that there is mixing of geothermal fluids and ground water in the area, and that the springs are sourced from the same geothermal reservoir. The Tarewa Stream outflow had a chloride concentration of 306 mgL^{-1} and probably presents a good average chloride concentration of the discharges in Kuirau Park. The water temperatures of pools ranged from near ambient 25 °C to boiling 99.9 °C, with most pool temperatures between 40 and 70 °C.

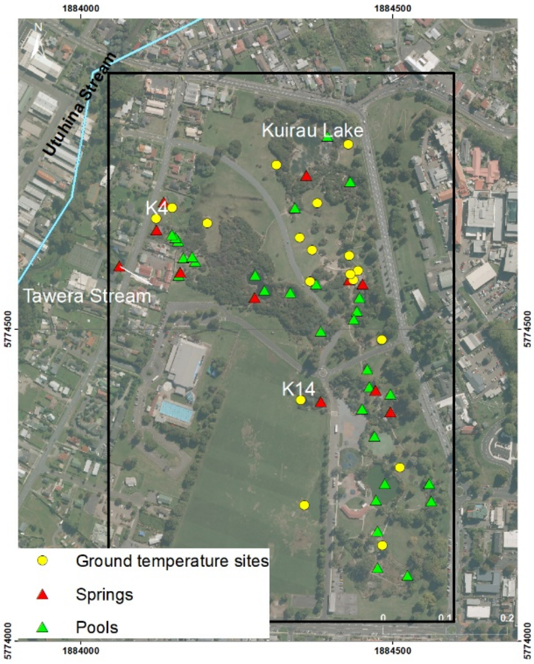

Figure 8: Survey sites located at Kuirau park

A calorimeter measurement was made on geothermally altered ground. A heat flux of 251 Wm^{-2} was determined. Ground temperature profiles showed that most of the ground was ambient, except for two sites which showed elevated ground temperatures (K4 and K14, Figure 8). Total surface heat flow from the ground in the area was calculated using the TIR image collected in 2014 (Reeves et al. 2014) to estimate land area of "like" ground. Table 5 lists the totaled measured heat flow from the different features in the Kuirau Park area.

Table 5: Measured heat flow from Kuirau Park geothermal area (~ 590 m^2).

	Measured Heat flow
Surface heat flow from pools	72.6 MW
Surface discharge from measured springs	0.02 MW
Estimated total surface heat flow through ground	0.7 MW
Total	**73.4 MW**

5.1 Uncertainties:

Uncertainty is incurred with potential errors in estimating the surface area of a pool. This was estimated in the field then corrected using a recent (2015/2016) aerial photograph. Care was taken to assess the surface area using these images, however there is some ambiguity in some pools due to shadows in the image. In these situations, personal knowledge and images collected by the field teams were used to interpret the pool surface area. Since there is natural variability in the water-level of pools over time especially between seasons, we assume that the surface areas presented in the project are accurate to within 10%.

Additional uncertainty arises from heat loss estimations assuming a constant surface temperature over the whole surface area of the pool. The temperature measured in one location is unlikely to be representative of the whole lake surface, especially in larger lakes such as Lake Roto-A-Tamaheke and Kuirau Lake (Figure 4 and Figure 8). TIR images (Reeves et al. 2014) show zones of hotter and cooler temperatures with apparent surface temperature differences of up to 5 °C on the surface of Lake Roto-A-Tamaheke.

6. SUMMARY AND CONCLUSIONS

The total heat loss for each area (excluding Ohinemutu and Ngapuna) in the RGF is summarised in Tables 1 - 5. The heat loss from discharging springs was smaller than the heat loss from pool surfaces and from steam-heated ground. The heat loss through discharging springs at Sulphur Bay is unaccounted for, as access to much of the area is unsafe due to unstable ground.

Arikikapakapa has no measurable spring discharges, with most heat loss derived from geothermal activity associated with large pools and mud features. This is similar to observations at Kuirau Park, where approximately 99% of the measured heat loss results from evaporative and radiated heat loss from pool surfaces.

Whakarewarewa contains the largest number of surveyed geothermal features and has significant volumes of geothermal water discharging into the Puarenga Stream. Calculated heat loss from Whakarewarewa into the Puarenga Stream is between 30 and 37 MW.

Total heat loss (evaporative, discharging flow, convective and conductive) for the areas surveyed is estimated to be 299 MW. This encompasses approximately 80% of the thermal areas in the Rotorua Geothermal Field. This result is lower than Glover's (1992) estimate of 470 ± 50 MW who uses a stream chloride flux method which has the advantage of estimating heat loss for the entire RGF, including geothermal seeps into Lake Rotorua (unlike the estimate presented here) but will underestimate total heat loss as it does not include evaporative or convective heat loss.

ACKNOWLEDGEMENTS

The authors would like to thank Bay of Plenty Regional Council for releasing the data and findings from the 2018 Surface Heat Loss of the Rotorua Geothermal Field study which forms the basis of this paper. The "New Zealand's Geothermal Futures" research programme supported the writing of this paper.

REFERENCES

Adam EE, Cosler DJ, Helfrich KR. 1990. Evaporation from heated water bodies: predicting combined forced plus free convection. *Water Resources Research.* 26(3):425-435.

Allis, RG., Lumb JT. 1992. The Rotorua Geothermal Field, New Zealand: its physical setting, hydrology and response to exploitation. Geothermics. 21 (1-2), 7-24

Bibby, HM., Caldwall, TG., Davey, FJ., Webb TH. 1995. Geophysical evidence on the structure of the Taupo Volcanic Zone and its hydrothermal circulation. JVGR. 68(1-3), 29-58

Bradford E, Glover RB. 1984. Heat and chloride inflow into the Puarenga Stream for Whakarewarewa. In: *Proceedings of the 6th New Zealand Geothermal*

Workshop; 1984 Nove 7-9; Auckland, New Zealand. Auckland (NZ): Geothermal Institute.

Bromley CJ, van Manen SM, Mannington W. 2011. Heat flux from steaming ground: reducing uncertainties. In: *Proceedings, 36th Workshop on Geothermal Reservoir Engineering;* 2011 Jan 31-Feb 2; Stanford, CA. Stanford (CA): Stanford University. p. 925-931.

Cody, AD., Lumb JT. 1992. Changes in thermal activity in the Rotorua geothermal field. Geothermics. 21 (1-2) 215-230

Cody A, Simpson B. 1985. Natural hydrothermal activity. In: New Zealand Department of Scientific and Industrial Research. *The Rotorua geothermal field: technical report of the Geothermal Monitoring Programme 1982-1985*. Wellington (NZ): Ministry of Energy, Oil and Gas Division. p. 227-273.

Dawson GB. 1964. The nature and assessment of heat flow from hydrothermal areas. *New Zealand Journal of Geology and Geophysics.* 7(1):155-71.

Ellis. AJ., Wilson, SH. 1955. The Heat from the Wairakei – Taupo Thermal Regime calculation from Chloride Output. NZ Journal of Science and technology 36(B), 622-31

Fridriksson T, Kristjansson BR, Armannsson H, Margretardottir E, Olafsdottir S, Chiodini G. 2006. CO_2 emissions and heat flow through soils, fumaroles, and steam heated mud pools at the Reykjanes geothermal area, SW Iceland. *Applied Geochemistry*. 21(9):1551-1569. doi:10.1016/j.apgeochem.2006.04.006.

Glover RB. 1988. Chemical and physical changes in the outflow from Whakarewarewa to the Puarengua stream, Rotorua. In: *Proceedings of the 10th New Zealand Geothermal Workshop*; 1988; Auckland, New Zealand. Auckland (NZ): Geothermal Institute. p. 269-273.

Glover RB. 1992. Integrated heat and mass discharges from the Rotorua geothermal system. *Geothermics*. 21(1-2):89-96.

Hochstein MP, Bromley CJ. 2005. Measurement of heat flux from steaming ground. *Geothermics*. 34(2):131-158.

Miotti L, Mroczek E, Hurst T. 2010. Review of heat flow surveys at Whakarewarewa. Lower Hutt (NZ): GNS Science. 28 p. (GNS Science report; 2010/41).

Ratouis TMP, O'Sullivan MJ, O'Sullivan JP. 2016. A numerical model of Rotorua geothermal field. *Geothermics*. 60:105-125.

Reeves RR, Rae L. 2016. Changes in aerial thermal infrared signature over the Rotorua Geothermal Field, New Zealand: 1990–2014. *Geothermics*. 64:262-270. doi:10.1016/j.geothermics.2016.06.007.

Reeves RR, Scott BJ, Hall J. 2014. 2014 Thermal infrared survey of the Rotorua and Lake Rotokawa-Mokoia Geothermal Fields. Lower Hutt (NZ): GNS Science. 28 p. (GNS Science report; 2014/57).

Ryan PJ, Harleman DRF, Stolzenbach KD. 1974. Surface heat loss from cooling ponds. *Water Resources Research.* 10(5):930-938.

Sartori E. 2000. A critical review on equations employed for the calculation of the evaporation rate from free water surfaces. *Solar Energy*. 68(1):77-89.

Scott BJ, Mroczek EK, Burnell JG, Zarrouk SJ, Seward A, Robson B, Graham DJ. 2016. The Rotorua Geothermal Field: an experiment in environmental management. *Geothermics*. 59(B):294-310. doi:10.1016/j.geothermics.2015.09.004.

Seward, AM, Sanders, F., Mroczek, E., Reeves, R., Bromley. C.,Brakenrig, T., Macdonald, N., Graham, D. and Lor, S. 2018a. Rotorua heat flow survey 2018. Wairakei (NZ): GNS Science 63p (GNS Science consultancy report; 2018/94)

Seward A, Ashraf S, Reeves R, Bromley C. 2018b. Improved environmental monitoring of surface geothermal features through comparisons of thermal infrared, satellite remote sensing and terrestrial calorimetry. *Geothermics.* 73:60-73. doi:10.1016/j.geothermics.2018.01.007.

Simpson B. 1985. An assessment of heat flow at Whakarewarewa. In: *Proceedings of the 7th New Zealand Geothermal Workshop;* 1985 Nov 6-8; Auckland, New Zealand. Auckland (NZ): Geothermal Institute. p.147-148.

Sorey ML, Colvard EM. 1994. Measurements of heat and mass flow from thermal areas in Lassen Volcanic National Park, California, 1984-93. Denver (CO): U.S. Geological Survey. 35 p. Water Resources Investigations Report No.: 94-4180-A.

Wilson, CJN, Rowland, JV. 2016. The Volcanic, magmatic and tectonic setting of the Taupo Volcanic Zone, New Zealand, reviewed from a geothermal perspective. Geothermics 59(B). 168-187

ISSN 2703-4275