MODERN HEAT FLOW ESTIMATES OF WHAKAREWAREWA GEOTHERMAL VALLEY, ROTORUA

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ABSTRACT

The Rotorua Geothermal Field (RGF) covers a surface area of approximately 18-28 km^2 in the northwest region of the Taupo Volcanic Zone (TVZ). With an estimated natural heat-flow of 430 MW, the RGF is considered one of the larger geothermal systems within the TVZ. The RGF underwent a period of development and exploitation during the 1970s utilising fluids from the shallow (<300m depth) aquifer. The mass withdrawal and consequent pressure reduction in the shallow part of the system resulted in diminished discharge and extinction of some natural surface features located around the Rotorua Township. A government-enforced bore-closure program was introduced in 1986 to manage and reduce effects of development on the shallow geothermal reservoir.

Heat flow calculations from natural surface features are used to estimate the size of the geothermal reservoir and provide an insight into the health of the geothermal system. In 2010 a heat flow survey was undertaken by measuring temperatures and water flow of selected water features at Whakarewarewa, located on the southern boundary of the RGF. Lake Roto-a-Tamaheke is the largest geothermal feature in the Whakarewarewa area. This paper presents data and heat flow estimates for the Lake Roto-a-Tamaheke area and compares the heat flow measurements to previous estimates.

1. BACKGROUND

1.1 Rotorua Geothermal Field - Geological Setting

The Rotorua Geothermal Field (RGF) is located in the northwestern region of the Taupo Volcanic Zone (TVZ) in the central North Island of New Zealand (Figure 1) and covers a surface area of ~18 - 28 km^2 (Bibby et al, 1995). The TVZ is an area known for its volcanic and geothermal activity resulting from the high heat flow of the back-arc rifting. The total crustal heat transfer of the TVZ has been estimated to be approximately 2600 MW/100km^2 (Hochstein, 1995).

The natural surface heat flow of the RGF is one of the largest of the geothermal systems within the TVZ with a total heat flow of approximately 430 MW (Glover, 1992).

The RGF is famous for its numerous natural geothermal surface features which are generally located in three regions of the City; (1) Whakarewarewa and Arikikapakapa to the south of the city, (2) Kuirau Park and Ohinemutu to the north, and (3) Government Gardens, Sulphur Bay and Ngapuna to the northeast (**Figure 2**). The most spectacular and well-known surface features occur at Whakarewarewa. Lake Roto-a-Tamaheke is the largest water-body at Whakarewarewa, located in the northeastern margin of the geothermal area (**Figure 3**). This feature is the most dominant feature in terms of heat loss at Whakarewarewa .

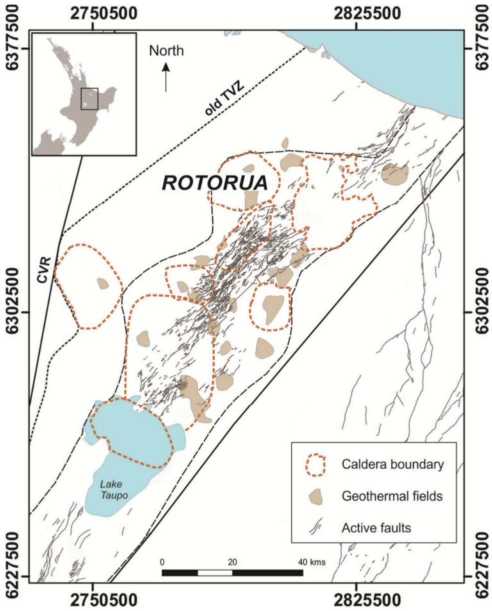

Figure 1: Map of the TVZ showing the locations of the geothermal fields (Bibby et al, 1995), volcanic caldera boundaries (Wilson et al, 2009) and the known active faults (GNS Science, Active Fault Database) (modified from Chambefort et al, 2014).

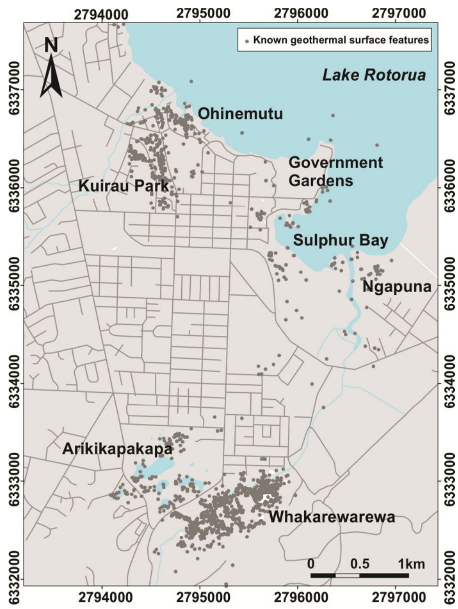

Figure 2: Location of known surface geothermal features in the RGF.

1.2 Exploitation History

Direct use of the geothermal heat has been utilised in Rotorua since the region was populated with traditional uses including heating, cooking and bathing. The first hot-water bores were drilled in the early 1930s, reaching more than 750 known wells by the 1970s (Allis and Lumb, 1992) which tapped the shallow geothermal aquifer mainly for domestic and commercial heating. By 1985 the draw-off from the geothermal wells averaged 31,000 ton/day during winter months, almost double the natural flow from Whakarewarewa, (~17,000 ton/day) (Gordon et al, 2001). This resulted in a noticeable decline in activity of the surface features around the city that led to the introduction of the Rotorua Geothermal Monitoring Programme (RGMP) in 1985 (Mahon, 1985). The RGMP saw over 100 producing wells closed within 1.5 km radius of Pohutu Geyser (Figure 3), with another 200 wells closely monitored around the city. These enforced closures and regimented used resulted in a 70% decrease in draw-off by 1989 (Allis and Lumb, 1992). Initial monitoring of the aquifer system suggested that there was an immediate response in rebounding pressure levels (e.g. Bradford, 1992a); although responses in temperature, chemistry and heat flow have not been so apparent (Seward, in prep).

This paper presents results from heat flow studies in 2010 and 2012 undertaken at Whakarewarewa.

2. HEAT FLOW

Heat flow is an estimate of the total amount of heat being transferred from either the ground or the surface of a water body into the atmosphere. The measurement of heat flow for a geothermal area is important for inferring the size of the heat source and hence the potential for size of the geothermal reservoir. Methods for estimating heat flow include: using chloride concentrations of geothermal waters (e.g. Glover, 1988, 1992); direct heat flow measurements using a calorimeter (e.g. Hochstein and Bromley, 2005) or using steam venturi (e.g. Dawson and Dickenson, 1970); determining soil-temperature gradients (e.g. Dawson, 1964; Bromley and Hochstein, 2005); and determining the heat loss from the surface of a water body (e.g. Dawson, 1964; Ryan et al, 1974; Adams et al, 1990).

Miotti et al (2010) and Bloomer (2012) outlined a comparison of different methods. Each method differs significantly from the others as many of the methods are built for a particular type of water feature. We tested how much variation there is in using the different methods outlined in Miotti et al (2010), by applying the equations of Dawson (1964), Hurst and Dibble (1981), and Adams et al (1990) to the data collected for Lake Roto-a-Tamaheke, and further compare the methods of Dawson (1964) and Adams et al (1990) for the features surrounding the lake. The method of Hurst and Dibble (1981) is designed for larger water bodies and not used here to analyse heat flow as Lake Roto-a-Tamaheke is the only feature where these equations can be applied.

Here we present heat flow calculated for ~ 20 water bodies in the proximity of Lake Roto-a-Tamaheke, using the methods of Dawson (1964), and Adams et al (1990) for estimations of heat loss through evaporation, conduction and convection. A generic heat loss from direct discharge is also used for the flowing features where a notable flow is measured.

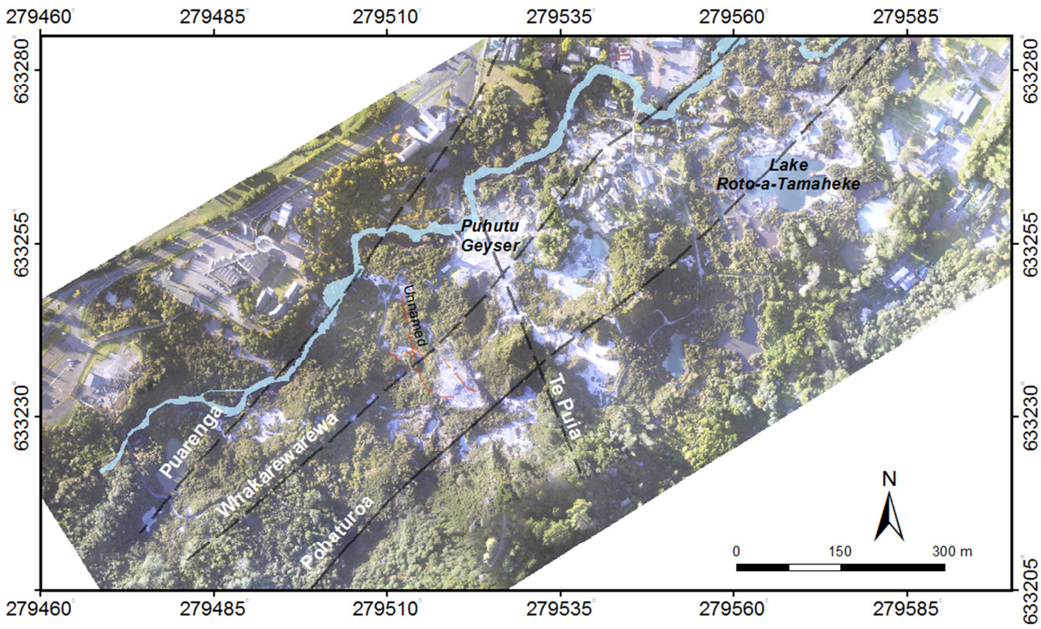

Figure 3: Aerial image of Whakarewarewa. Grey dashed lines show the locations of the 4 main known faults in the Valley, Puarenga, Whakarewarewa, Pohaturoa and Te Puia (Lloyd, 1975). Orange dashed lines indicate the potential locations of other smaller faults in the area (BOP_NZGD2000).

2.1 Dawson (1964) - Method for calculating heat flow from calm water body surfaces

Previous heat flow studies in the Whakarewarewa area (Cody and Simpson, 1985) have used the method outlined by Dawson (1964) to calculate heat flow from both hot water bodies and warm ground. When calculating heat flow from hot water bodies, Dawson (1964) focused on two mechanisms for heat loss. Firstly, the heat loss due to evaporation of the water surface and secondly, the radiated heat loss from the ground surface. Additional heat loss can occur through the conduction of heat between surface and air molecules, although it is very small compared to the heat loss through the radiation and evaporation processes. The total heat flow (Q_{tot}) can be estimated by

$$Q_{tot} = Q_E(1 - R) + Q_R$$

where Q_E is the heat loss due to evaporation on a flat (calm) surface (KJ/hr), Q_R is the heat loss due to radiation (KJ/hr) and R is Bowen's ratio that is used to estimate the effect of the conductive heat loss.

Heat loss due to evaporation can be calculated by

$$Q_E = M * A * h_f(T_W)$$

where M is the rate of evaporation (kg/m^{2}hr), A is the surface area of the pool (m^2) and $h_f(T_w)$is the specific enthalpy of saturated liquid at water temperature T_w (ºC).

The rate of evaporation is directly related to the (W) in m/s and the saturated vapour pressure (in mm Hg) of both the water surface (ρ_s) and the atmosphere (ρ_a)

$$M = (0.031 + 0.0135W)(\rho_s - \rho_a)(760/p)$$

where p is the atmospheric pressure in mm Hg.

The radiated heat loss can be calculated from,

$$Q_R = 4.184 * E * A$$

where the radiated energy, E (W/m^2), can be calculated by adapting the Stefan-Boltzmann law for radiation from a black body by multiplying it by the emissivity (α) of water (=0.955)

$$E = \alpha * C * (T_w^4 - T_a^4)$$

with C *as* the Stefan-Boltzmann constant (5.6703 x 10^{-8} W/m^{2}K^4) and T_w and T_a are the temperatures (K) of the water and the air, respectively.

Heat loss to the atmosphere by conduction through the air and by molecular diffusion is minimal and is included in the heat loss calculation through the use of Bowen's ratio, the fraction of conductive heat loss (Q_{cd}) within the total evaporative heat loss (Q_e) (both in KJ/hr)

$$R = \frac{Q_{cd}}{Q_E} = (6.1 \times 10^{-4})\left(p\frac{T_s - T_a}{\rho_s - \rho_a}\right)$$

where, T_s is the temperature (ºC) of the water surface.

2.2 Adams et al (1990) - Method for calculating evaporative heat flow from calm water bodies

Adams et al (1990) combined free and force convection to estimate evaporative heat flux. Traditionally, these terms are added (e.g. Dawson, 1964; Ryan et al, 1974), however Adams et al (1990) propose to combine terms by the square root of the sum of squares showing that it can accurately estimate heat flow in several case studies of measured evaporation.

The free convective term assumes a constant horizontal heating surface, similar to that of a hot plate on a stove top. The whole surface area is consistent, and results in an evaporative heat loss calculated by

$$Q_{free} = 2.7(T_w - T_a)^{1/3}(e_s - e_a)$$

where Q_{free} is given in W/m^2; T_w and T_a are the water and air temperature (ºC), respectively; and e_s and e_a are the near-surface and air vapour pressure (mbar).

The forced convective term (Q_{forced}) (W/m^2) considers a 2 dimensional flow over the water surface and considers environmental effects, such as wind speed on the rate of heat loss over the surface area of the water body

$$Q_{forced} = 5.1\,A^{-0.05}W_2(e_s - e_a)$$

where A is the surface area (hectares).

Adams et al (1990) estimates the total heat loss of a water body by combining the forced and free convective terms as the square root of the sum of squares:

$$Q_{tot} = \left[\left(2.7(T_w - T_a)^{1/3}\right)^2 + (5.1A^{-0.05}W)^2\right]^{1/2}(e_s - e_a)$$

2.3 Miotti et al (2010) - Method for calculating heat flow from direct discharge of flowing water

The estimation of heat flow (Q) from springs or pond overflow is calculated by:

$$Q = F * h_f(T_w)$$

where F is the measured flow rate in l/s, and $h_f(T_w)$ is the enthalpy calculated from the specific heat capacity of the water.

3. DATA COLLECTION

In 2010-2011 a heat flow survey was conducted at Whakarewarewa (Figure 4). 420 ground temperatures were measured at 140 locations with several additional measurements made outside of the geothermal area for calibration. Temperatures and surface areas of water bodies were also collected so that heat loss could be estimated (Seward, in prep). Water flow rates of flowing features were also estimated where applicable.

In 2012, a follow up survey was undertaken focusing on the Roto-a-Tamaheke area (Prieto et al, in prep). 49 water features were surveyed (Figure 5), with their temperature, surface area and flow rates recorded.

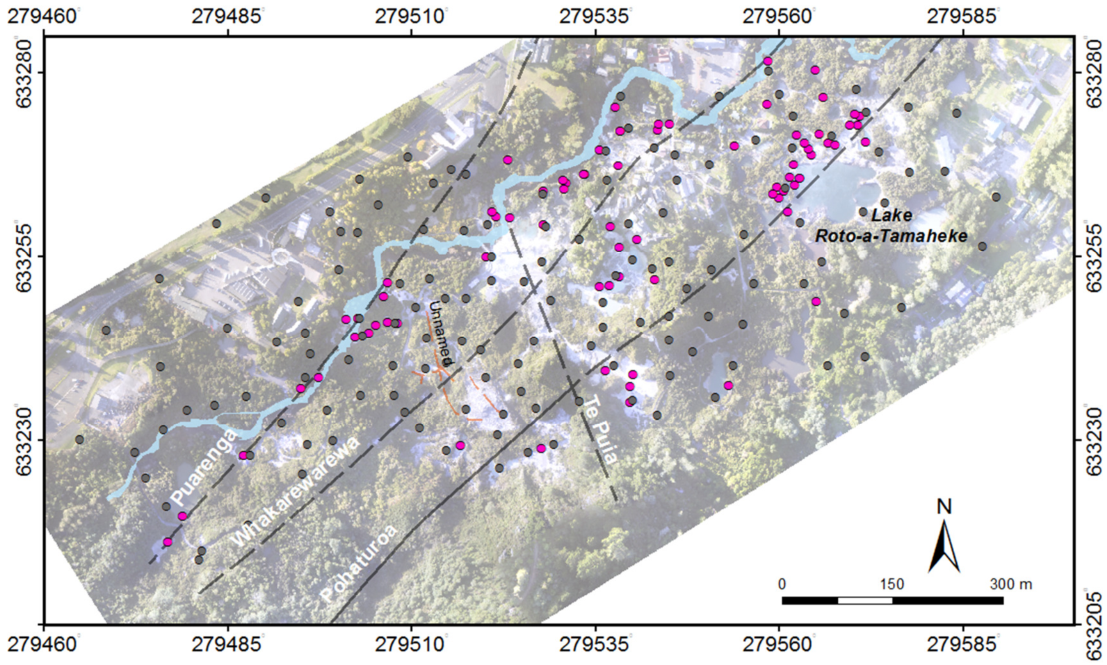

Figure 4: Locations of temperature measurements taken at Whakarewarewa , 2010-2011. Grey dots show location of ground temperatures, pink dots show location of water measurements (Seward, in prep). Black dashed lines show the known fault in the region, orange dashed lines shows the potential location of smaller faults (Lloyd, 1975).

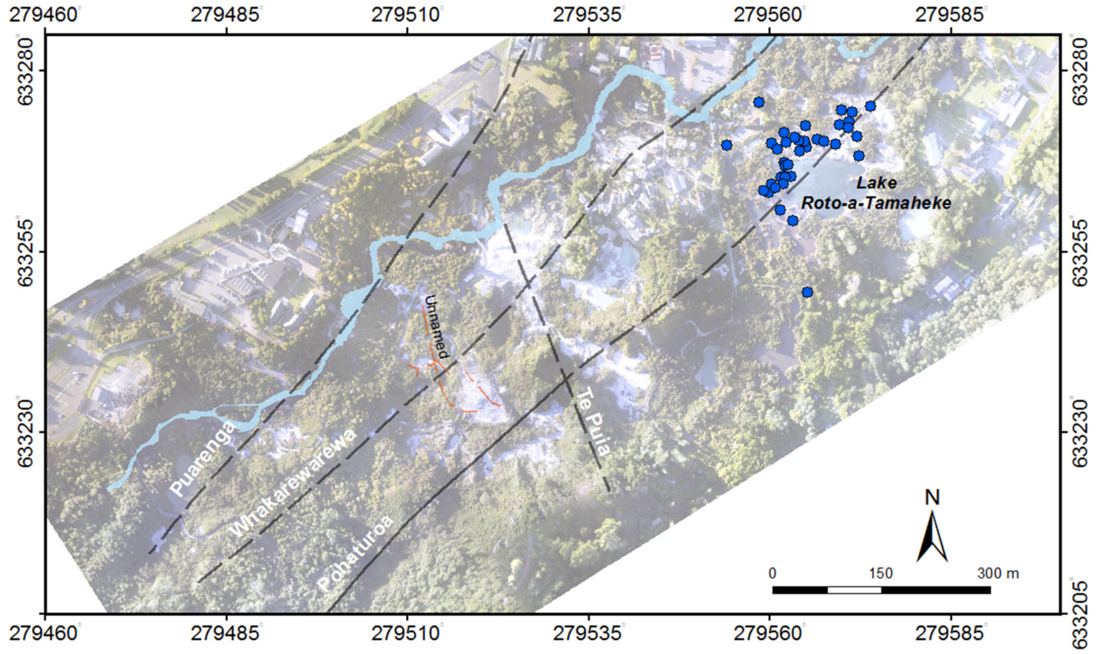

Figure 5: Locations of temperature measurements taken around Lake Roto-A-Tamaheke , 2012 (Prieto et al, in prep).. Black dashed lines show the known fault in the region, orange dashed lines shows the potential location of smaller faults (Llyod, 1975).

Table 1: Comparison of heat flux calculations for Lake Roto-A-Tamaheke using the methods of Dawson (1964), Hurst and Dibble (1981), and Adams et al (1990).

Survey	Temperature (°C)	Area (m^2)	Dawson (1964) (kW)	Hurst and Dibble (1981) (kW)	Adam et al (1990) (kW)
2010-2011	40	8,000	9,417	4,852	4,610
2012	44.4	8,000	10,679	7,100	6,335

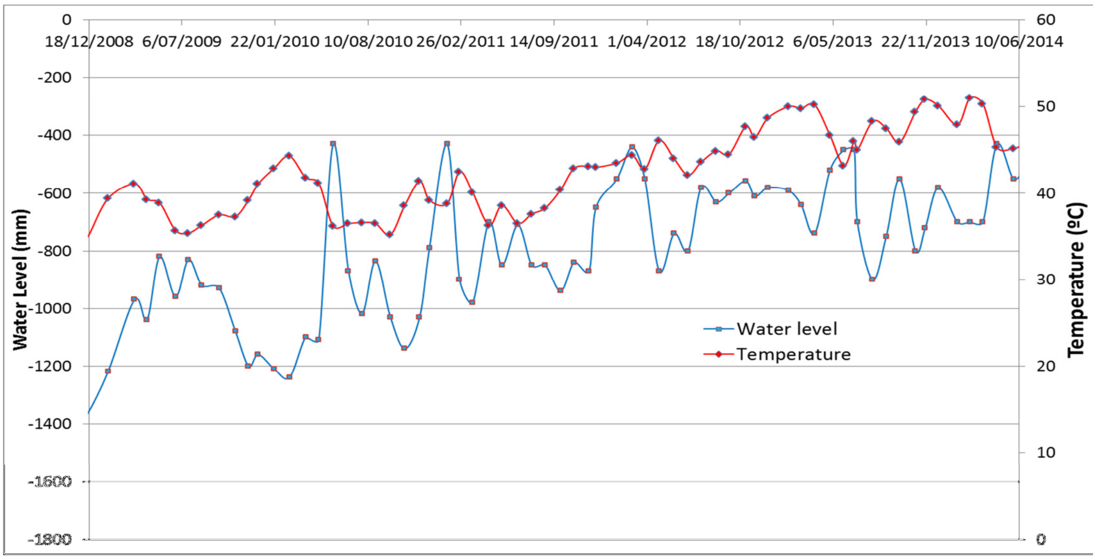

Figure 6: Measurements of temperature (red line) and water level, with respect to a datum point (blue line) for Lake Roto-A-Tamaheke, taken approximately monthly between May 2008 and June 2014. Data from Bay Of Plenty Regional Council (BOPRC)

4. RESULTS

Results are shown in Table 1 with an assumed constant wind speed of 1 m/s and a constant atmospheric reference temperature of 12 ºC. It is evident that results vary significantly depending on the method of calculation. While, the results from Dawson's methods allow modern heat flow estimates to be compared to historic published data (e.g. Cody and Simpson, 1985; Seward, in prep), Miotti et al (2010) suggests that the equations of Adams et al (1990) give a more accurate estimate.

4.1 Lake Roto-A-Tamaheke observations

Monthly measurements for Lake Roto-a-Tamaheke between 2008 and 2014 (Figure 6) show a gradual but steady increase in both temperature and water level (BOPRC monthly monitoring data, 2014). These observations suggest both an increase in temperature and water pressure of the shallow geothermal aquifer beneath Whakarewarewa during this time. Similar trends were noted by Bradford (1992b), when looking at overflow from Lake Roto-a-Tamaheke between 1984 and 1989. This observation was followed by an observed decrease in heat flow from the lake in 1990.

Historic temperature measurements for heat flow surveys undertaken in 1969 and 1984 of Lake Roto-a-Tamaheke suggest that lake temperatures were higher in the past, 64ºC and 49ºC respectively (Lloyd, 1969; Cody et al, 1984). This cooling is assumed to be associated with the increase draw-off from reservoir fluids through the increase in number of extraction bores around the city of Rotorua. Although the temperature of the lake and numerous other geothermal features did not respond immediately to the closure of the neighboring bores, the apparent steady increase in both temperature and lake level over the last six year suggests potential increase in the geothermal aquifer.

4.2 Heat flow for the Lake Roto-a-Tamaheke area

Measurements of heat flow allow the size of a heat source to be estimated. We compare the heat flow estimated for the Lake Roto-a-Tamaheke area, by comparing heat loss through conduction, convection and evaporation from the water surfaces of 19 geothermal features. Table 2 lists the observations and heat flow estimates from the 2010 and 2012 surveys.

Comparisons of common features over time, regardless of calculation method, show a general increase in heat flow for this region, with the main influence being the measured increase in temperature of Lake Roto-a-Tamaheke. Measured increases in temperature in several of the surrounding features also influence the overall heat flow estimations. A difference of total heat flow calculated using Dawson's (1964) equations show an increase in heat flow from 12,625 kW to 13,684 kW between 2010 and 2012, while heat flow calculated using Adams et al (1990) method suggest and increase in heat flow from 6,294 kW to 8,201 kW over the same time period.

5. DISCUSSION AND CONCLUSIONS

Despite the numerous methods in the literature to estimate heat loss from water surfaces through radiation, evaporation and conduction, most methods general follow the same pattern. The evaporative component is proportional to the saturation pressure, which is dependent on the temperature of the water body, while the radiated heat loss is proportional to the fourth power of absolute temperature. It is not surprising then, that the rate of heat loss is seen to increase with an increase in water temperature. Environmental factors such as air temperature, humidity, solar radiation and wind speed also affect the rate of heat loss from the surface of a water body.

This paper presents heat loss estimations for several features in the proximity of Lake Roto-a-Tamaheke at Whakarewarewa, Rotorua. Heat loss was calculated assuming consistent environmental factors so that the influences of seasonal variations do not affect the outcome and an average annual heat flow is estimated. An increase in heat flow is observed between 2010 and 2012. Historic heat flow estimations from surveys undertaken in 1969 (Lloyd, 1969) and 1985 (Cody et al, 1985), for the same 19 geothermal features, show a dramatic decrease in total heat flow since the 1969 survey (pre-exploitation), the majority of which occurred in the 15 years of increased exploitation prior to 1985 (Table 3).

Table 2: Heat flow data measured in the Lake Roto-a-Tamaheke area in 2010 and 2012.

Feature ID	Survey	Water Temperature (ºC)	Surface Area (m^2)	Flow Rate (l/s)	Dawson's' Heat flow (kW)	Adams et al, Heat flow (kW)	Direct discharge Heat flow (kW)
328	2010	39	770		851	427	
	2012	45	700		948	582	
337	2010	40	8,000		9,417	4,610	
	2012	44	8,000		10,679	6,335	
351	2010	70	1.5		8	6	
	2012	40	4		6	3	
359	2010	17	50		5	2	
	2012	10	70		1	1	
365	2010	30	25		14	7	
	2012	71	23		125	89	
372	2010	65	5	0.1	22	15	22
	2012	42	5		8	4	
377	2010	56	6		17	11	
	2012	53	6		16	9	
378	2010	73	4		34	18	
	2012	90	6		78	57	
380	2010	65	5		22	15	
	2012	100	2		42	28	
381	2010	76	12		83	59	
	2012	83	9		13	63	
382	2010	73	4		33	17	
	2012	94	4		62	45	
392	2010	96	9		140	110	
	2012	98	9		152	119	
396	2010	80	60		500	357	
	2012	74	40		246	180	
400	2010	65	10		43	29	
	2012	86	9		95	70	
429	2010	65	2		9	6	
	2012	70	4		25	15	
430	2010	26	40		34	17	
	2012	30	33		17	9	
431	2010	77	4		29	21	
	2012	77	1		12	5	
443	2010	33	1,080		805	373	
	2012	31	1,080		561	304	
447	2010	20	3,000	2.2	560	196	70
	2012	22	2,770	0.2	598	282	8

Table 3: Total heat flow changes over time for 19 water bodies in the proximity of Lake Roto-a-Tamaheke. Bracketed numbers show the percentage of heat flow relative to the 1969 values.

Year	Heat flow (kW) (Dawson 1964)	Heat flow (kW) (Adams et al 1990)
1969	39787	24436
1985	23639 (59%)	13041 (54%)
2010	12625 (31%)	6294 (26%)
2012	13684 (34%)	8201 (34%)

The calculated heat flow calculated from Dawson's equations decreased by 41% between 1969 and 1985, and a further 28% by 2010. Over the following two year an increase 3% of the pre-exploited heat flow is seen. When using the Adams et al (1990) equations, similar numbers are seen for these features: a decrease of 46% over the initial 15 years, followed by a further 18% decrease over the next 25 years, and an increase of 8% between 2010 and 2012.

It is apparent that although the current heat flow is still only a fraction of the heat flow from these features seen prior to exploitation of the shallow aquifer, the recent increase seen between 2010 and 2012 could suggest that the geothermal system may be showing signs of recovery. However given the large uncertainties associated with calculating heat flow, the small increase in heat seen between 2010 and 2012 may be statically insignificant. Without a follow up survey of Whakarewarewa, the significance of the recent observed increase in heat flow cannot be determined.

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