THE HEAT DISCHARGE INTO LAKE ROTOMAHANA, NORTH ISLAND, NEW ZEALAND

P.C. Whiteford and H.M. Bibby

Institute of Geological and Nuclear Sciences, Wellington, New Zealand

Key words: Heat flow, lake Rotomahana, New Zealand

ABSTRACT

Modern Lake Rotomahana was formed during the 1886 eruption of Mt Tarawera. Heat flow measurements made in the bottom sediments using a marine temperature probe indicate a thcrmal area in the south-western half of the lake which has a total condrictivc heat flow of 19 MW. The convective heat discharged into the lake, calculated from tlie rate of incrcase in temperature of the lake, is estimated to bc 175 **145** MW. The ratio of conductive to convective heat flow is similar to that measured in the thermal areas beneath Lake Rotorua, North Island, New Zealand.

INTRODUCTION

The Taupo Volcanic Zone in the North Island, New Zealand (Fig. 1) is a volcanic belt extending from the volcanoes, Mt Ruapehu and Mt Ngauruhoe, in the southwest to Whale Island and White Island offshore to the northeast. Lake Rotomahana is one of the southernmost of the Rotorua lakes, lying within the Taupo Volcanic Zone 2 km south of Lake Tarawera and 5 km southwest of Tarawera volcano. To the southwest is the Waimangu thcrmal area (Fig. 2), which contains active thermal features such as hot or boiling pools, silica deposits, steaming cliffs, and hot ground, and is a well known tourist spot for viewing thermal activity. It is thought that a substantial portion of tlie total heat output of the Waimangu thermal system occurs through the floor of Lake Rotomahana. Despite this, no estimate has been made of this component of the heat.

Lake Rotomahana lies within the crater that formed during the 1886 Tarawera eruption which claimed 108 lives. Before 1886, there were two small lakes in the area now occupied by Lake Rotoinahana (former Lake Rotomahana and Lake Rotomakariri, Fig. 2), and this region was the most intensely active hydrothermal field in the Rotorua district (Keam, 1988, Nairn, 1989. Scott, 1992). During the Tarawera eruption a 17 km long fracture formed extending from Mt Tarawera through Lake Rotomahana to tlie Waimangu thermal area. Violent steam and lava eruptions deepened and enlarged the two small lakes to form Rotomahana Crater, which was the site of vigorous steam emission until it filled with water to form the present Lake Rotomahana. Tlie famous Pink and White Terraces were either destroyed or covered in the I886 eruption and Lake Rotomahana now covers the locality of these terraces (Keam, 1988).

Lake Rotomahana has no surface outlet. Subsurface flows through thick volcanic ash deposited in 1886, however, provide drainage from Lake Rotomahana into Lake Tarawera. The lake covers an area of 7.95 km^2, has a maximum length of 6.2 km a width of 2.8 km, and a maximum depth of 125 m (Irwin, 1975). The lake bathymetry is shown in Fig. 2.

Present-day thermal activity near Lake Rotomahana occurs mainly in two zones: along the western shore of the lake where

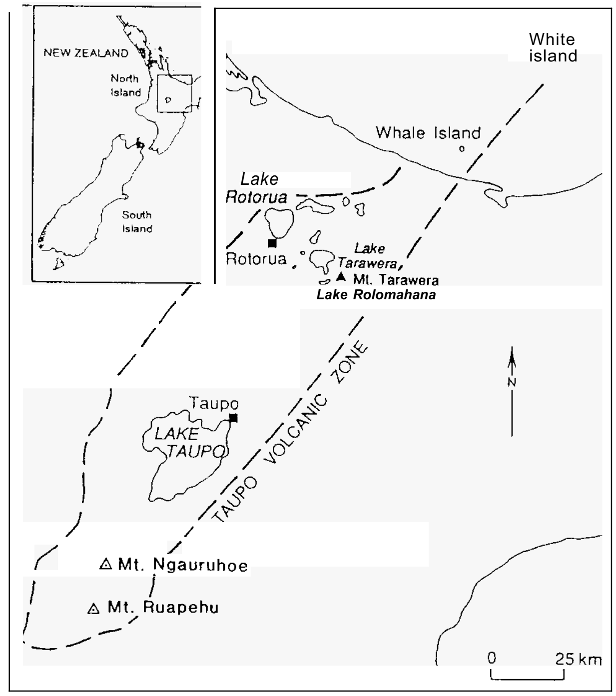

Figure 1. Map showing the location of ***Lake*** *Rotomahana in* ***the*** *North* ***Island*** *of New Zealand.*

there are extensive tracts of altered ground, fumaroles, boiling springs, geysers; and along the southern shore where minor hydrothermal activity in the form of warm and hot springs occur close to lake level (Nairn, 1989). Activity close to the lake fluctuates with lake level. Nairn (1989) reports large upwellings of hot water in the lake 10-20 m offshore which may indicate the locations of major submerged hot springs. In the eastern part of the lake there is no surface thermal activity but there is a discharge of cold gas rising through the lake at one spot.

During a survey of lake water temperatures Jolly (1968) noted that the lake was 3°C warmer than nearby Lake Tarawera (1 km to the north). and attributed this to the explosive origin of the lake but the actual heat source was not identified. Jolly found no significant spatial variation in bottom water tempcratures. A later survey by Irwin (1968) at 63 measurements sites, distributed with even and relatively dense coverage, showed that at all sites water was isothermal (15.8°C) from 1 m above the bottom to within 40 m of the surface, and that at all but 5 sites the water was isothermal from the bottom to 40m depth. At three sites, elevated temperatures were observed at the bottom in water about 80 m deep in the southern part of the lake (23.3°C, 23.9°C, and 37.7°C, Fig. 2). At two other sites slightly elevated temperatures (18.0°C, 18.3°C) were observed at the bottom. Irwin (1968) also noted that lake temperature was 4 to 5°C higher than similar nkarby lakes, which he attributed to local heat input from tlie lake floor.

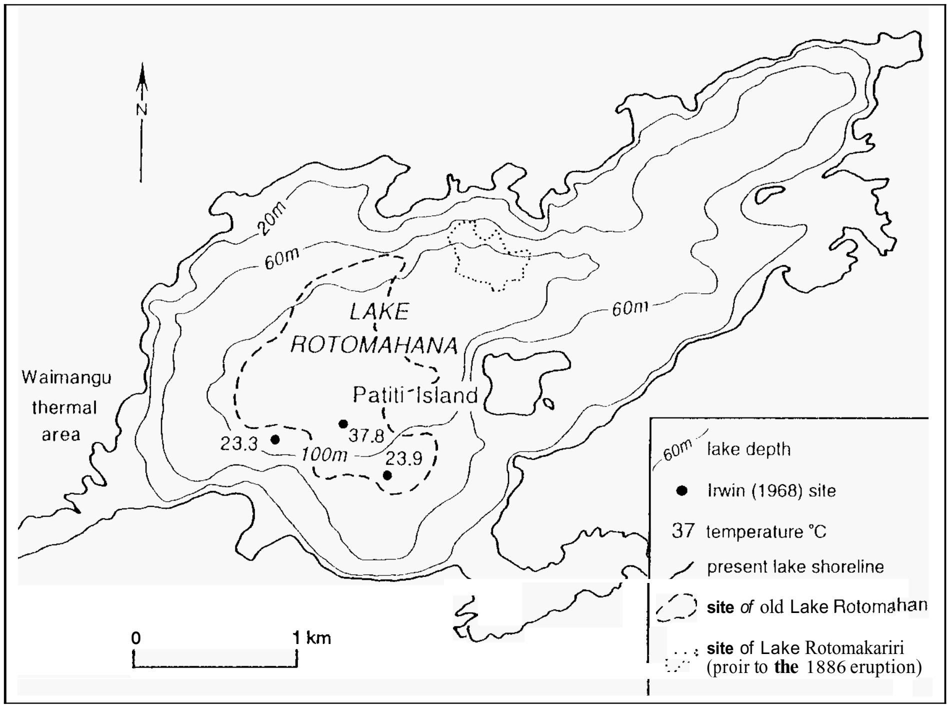

Figure 2. Bathymetry (m) of Lake Rotomahana and the location of and the temperatures at the three sites where Irwin (1968) measured high bottom water temperatures. Elsewhere Irwin (1968) measured bottom water temperatures of 15.5°C.

In October 1992, 28 heat flow measurements were made in the bottom sediments of Lake Rotomahana to delineate and measure areas of high heat flow (Fig. 3) (Whiteford & Graham, 1994). The measurements indicated a total conductive heat output of 19 MW, and an average conductive heat flux three times higher than in the geothermal areas beneath Lakes Rotorua and Taupo. High heat flows (averaging 4 W/m^2) occurred in the south-west part of the lake over an area of 4.8 km^2, representing just over half the area of the lake. Very high heat flows (greater than 10 W/m^2 and up to 45 W/m^2) occurred in two parts of the high heat flow anomaly, one in the west which appears to be an extension of the active part of the Waimangu thermal area on the land; and the other in the southern part of the lake which appeared to be a separate entity. In the north-eastern remainder of the lake no high heat flows were measured.

The heat flow measurements enabled the conductive heat flow to be calculated. The convective heat flow had not been estimated, but it was noted that if the thermal system were similar to that beneath Lake Rotorua, then about 14 times the conductive heat may be discharged convectively into the bottom of the Lake Rotomahana (Glover, 1992, Whiteford, 1992a).

WATER TEMPERATURE MEASUREMENTS

Water Temperature Depth Profiles

Three water temperature-depth profiles were measured at widely spaced sites on 24 March 1992, prior to the heat flow measurements, and two measured on 28 October 1992 at the time of the heat flow measurements, also at widely spaced sites. These profiles are plotted in Fig. 4. The lake temperatures in October 1992 were colder than in March 1992 (Fig. 4) indicating that the lake had overturned and cooled during the winter of 1992. The profiles all indicate that a thermocline existed in the lake at the time of the measurements. In March it extended to a depth of about 35 m, whereas in October, spring, it extended to about 25 m. Below the thermocline water temperatures decrease very slowly and are almost the same across the lake. Irwin (1968) and Jolly (1968), also noted that deeper water temperatures were uniform across the lake. This uniformity of temperatures below the thermocline has been observed in many other New Zealand lakes (Irwin, 1968, Jolly, 1968, Irwin, 1971, Irwin & Jolly, 1970, Whiteford et al., 1992).

Bottom Water Temperatures

The bottom water temperatures were measured at 28 sites during the heat flow survey of Lake Rotomahana from 21 to 30 October 1992 (Fig. 5). Twenty of the measurements lie between 12.75°C and 12.87°C (Table 1), but the remaining eight have elevated bottom water temperatures of between 12.97°C and 15.83°C. Wherever close spaced observations are available the elevated temperatures are very localised, as bottom water temperatures are not elevated at sites as close as 100 m. These regions of elevated bottom water temperatures are believed to be sites at which geothermal waters enter the lake from below. There is no evidence for extensive areas of geothermal fluid discharge. This

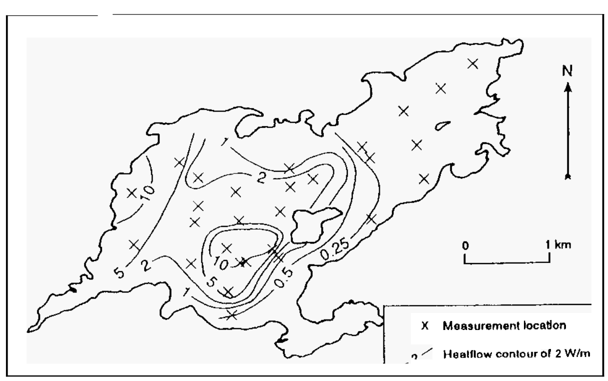

Figure 3. Contours of heat flow (W/m^2) for the sediments of Lake Rotomahana. The contours are at 0.5, 1, 2, 5, & 10 (W/m^2).

is confirmed by Irwin's (1968) water temperature measurements which also showed that elevated bottom water temperatures were very localised.

Over the period of observation, it was noticed that the bottom water temperatures appear to increased gradually by about 0.1°C. Such a systematic increase in temperature throughout tlic lake results from both tlic conductive and convective heat transfer into the lake waters. Quantifying this change thus presents a means of estimating tlie total heat output through tlie lake floor.

In order to quantify the rate of temperature increase of the lake as a whole, the data (less those measurements showing evidence of lying close to thermal vents) were analysed using a least squares technique. In addition to the variation of temperature with time, it was recognised that the temperature may be uniformly higher in some parts of the lake. Similarly, as has already been observed, a small variation in temperature also occurs with depth. Consequently. the analysis allowed for variations of temperature with position, depth and time. Results of this analysis arc shown in Table I.

The greatest correlation of water bottom temperature with position occurs along an axis with azimuth of 80". This strong correlation of temperature with position reflects the greater heat input to the south of tlie lake, shown in Fig. 3. Although the coefficient for the variation of temperature with depth has a very high standard error, the calculated gradient of 0.2°C/km is similar to that observed in the temperature profiles of Fig. **4.**

The temperature increase with time is computed to be 0.011 ± 0.003°C/day or 90 ± 25 days/°C. The analysis is surprisingly robust, with subsets of the data providing very similar estimates for the rate of temperature increase with time.

CALCULATION OF HEAT DISCHARGED INTO THE LAKE

The heat causing the temperature rise of tlie lake could come from several sources: the heat transferred from solar radiation

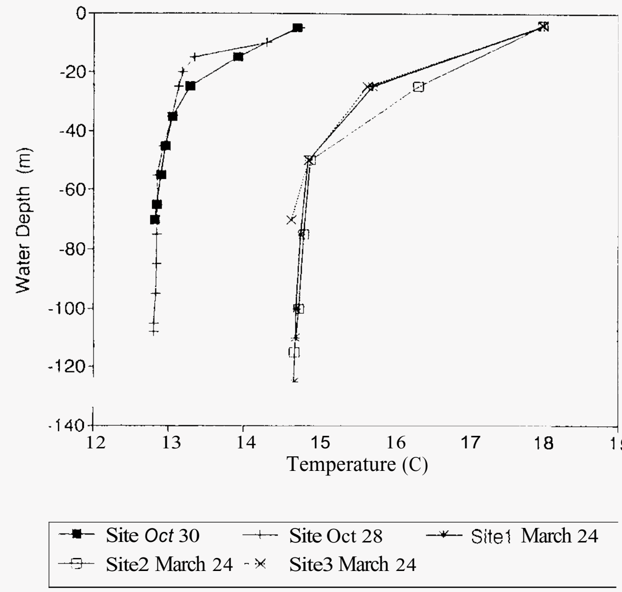

Figure 4. *Water temperature depth profiles measured in* ***Luke*** *Rotomahana in March and October 1992.*

Table 1 Results from the least squares analysis of the bottom water temperatures. Temperatures were assumed to vary in the form:

$$T = T_o + \alpha x + \beta y + \chi z + \varepsilon t$$

Parameter		Coefficient	Standard error
T_o	°C	12.82	±0.05
a	°C/km	-0.003	±0.01
β	°C/km	-0.043	±0.02
χ	°C/km	-0.2	±0.5
E	°C/day	0.011	H.003

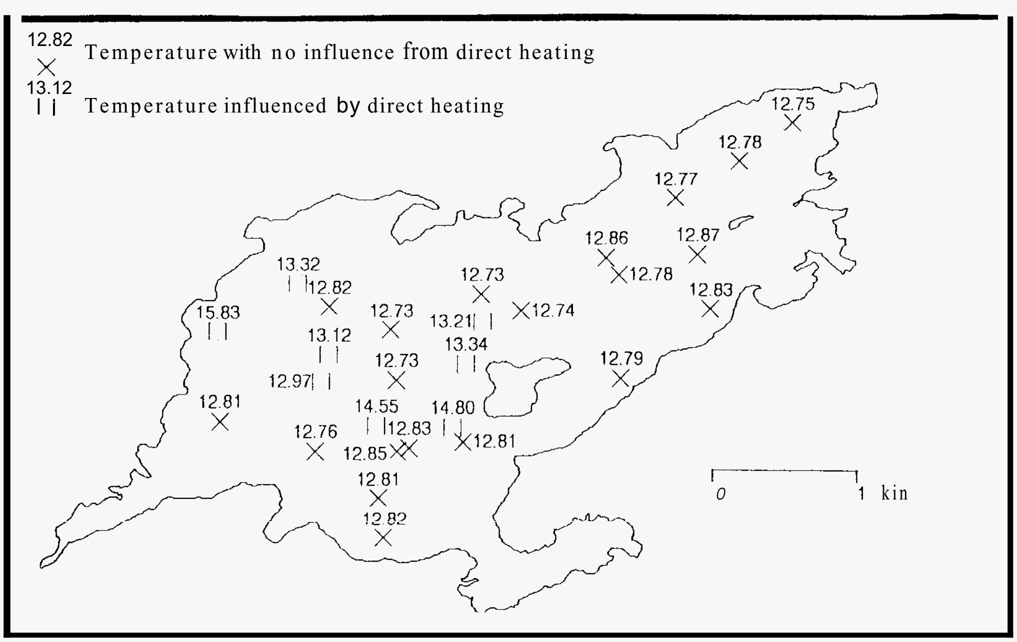

Figure 5. *Bottom water temperatures (°C) measured at 28* ***sites*** *in* ***Lake*** *Rotomahana from 21 to 30 October 1992.*

and warm surface air temperatures, the heat discharged into the lake as warm or hot streams from the Waimangu Thermal area, or the heat discharged into the water through the bottom of the lake, both convective and conductive.

As the temperature profiles show there is a distinct thermocline in Lake Rotomahana. The thermocline is a stable layer of warm water at the surface of the lake and there is no convective mixing with colder waters beneath. The water beneath the thermocline is essentially isolated from the thermocline. Heat transfer between the two bodies will occur by conduction but is a slow process and little heat is transferred. The thermocline is much deeper than expected for a lake of this size. Davies-Colley (1988) developed an empirical relationship between the depth of the thermocline and the size of the fetch for New Zealand lakes, and for Lake Rotomahana it gives a thermocline depth of 15m, which much less than the observed 25 to 35 m (Fig. 4). Streams containing thermal water discharge from Waimangu into Lake Rotomahana. The temperatures of these discharges are higher than the lake water beneath the thermocline. Hence the discharge waters do not sink through the thermocline but add to it, and give the unusually deep thermocline.

A little solar radiation may also get to the waters beneath the thermocline. The temperature rise in bottom waters due to transfer of heat from the thermocline and from solar heat input is likely to be no more than observed in Lake Taupo, a lake of similar depth but of much larger extent and more exposed to wind, and therefore more prone to mixing. At Lake Taupo the rise in bottom water temperatures over the period of about 8 months each year when a thermocline existed was about 0.3°C (Whiteford, 1992b). This is approximately 0.001°C/day, which is small compared with the observed heating at Rotomahana (Table 1), and can be neglected.

It is concluded that only significant heat input into the waters beneath the thermocline is from the thermal areas in the bottom of the lake

The energy input into the lake, (E), is calculated from the temperature rise using the relation

$$E = ms\,\delta T/\delta t$$

where m is the mass, s the specific heat of water (4187J/kg°C), and $\delta T/\delta t$ is increase in temperature with time. The total volume of the lake was estimated using the bathymetry map and is 0.51 km^3. The volume of the thermocline, for a depth of 25 m, is subtracted leaving a volume of 0.32 km^3. Using the observed rate of increase in temperature, the energy input is estimated to be 175±45 MW. This **is** 9 times the conductive component, of 19MW.

DISCUSSION

The high natural heat output is of similar magnitude to the natural heat output of many geothermal systems in the Taupo Volcanic Zone. The ratio of conductive to convective discharge is similar although less than that for Lake Rotorua where the conductive and convective heat flows were estimated to be 20MW and 280 MW respectively (Glover, 1992, Whiteford, 1992a).

No total estimate of the heat output of the Waimangu Geothermal System has previously been available. Scott (1992) estimate the heat output from surface features along the Waimangu valley to be 150 MW, comparable with that passing through the lake floor. Allowing for the lesser surface thermal features not included in Scott's assessment, the total energy output is about 400 MW. By way of comparison, if the total flow of geothermal waters from Waimangu is assumed to find its way into Lake Tarawera, the chloride flux passing through Lake Tarawera can be used to give an independent estimate of heat output. Finlayson and Nairn (1981) give a chloride flux for Tarawera of 454 g/s from which they estimated an energy flux of 360 MW. A more realistic enthalpy to chloride ratio for the Waimangu system (Sheppard, 1986) would raise this estimate **to** 500 MW. Either of these estimates would suggest that the heat input from the lake is in the correct order, despite the uncertainties involved.

The bottom water temperatures were measured over a relatively short time span of 10 days, which limited the accuracy of the estimate of total heat input. Ideally measurements should be made over a period of several months during the time when the thermocline is present and the lake waters are stable. This may also provide a test of the assumption that the amount of heat transferred from the thermocline to the water below the thermocline was insignificant.

ACKNOWLEDGMENTS

The writers wish to thank Duncan Graham and Andrew Rae for undertaking the fieldwork and D.J. Woodward, for helpful criticisms of the manuscript.

REFERENCES

Davies-Colley, R.J. (1988). Mixing depths in New Zealand Lakes. ***New Zealand Journal of Marine and Freshwater Research,*** Vol 22, pp. 517-527.

Finlayson, J.B. and Nairn, I.A. (1981). ***Chloride flux measurements in the Tarawera River system.*** Geothermal Circular JBF2. Department of Scientific and Industrial Research, Wellington.

Jolly, Y.H. (1968). The comparative limnology of some New Zealand iakes. ***N.Z. J. Marine & Freshwater Research,*** 2, pp. 214-259.

Keam, R. F. (1988). ***Tarawera.*** Published by R. F. Keam, Physics Department, University of Auckland, New Zealand, 472pp.

Glover, R.B. (1992). Integrated heat and mass discharges from the Rotorua geothermal system. ***Geothemics,*** vol. 21, pp. 89-96.

Irwin, J. (1968). Observations of temperatures in some Rotorua Lakes. ***N.Z. J. Marine & Freshwater Research, 2,*** pp.591-605.

Irwin, J. (1975). ***Checklist of New Zealand Lakes.*** New Zealand Oceanographic Institute Memoir 74, New Zealand D.S.I.R., Wellington, New Zealand.

Irwin, J. (1971). Exploratory limnological studies of Lake Manapouri, South Island, New Zealand. ***N.Z. J. Marine and Freshwater Research*** 5(1), pp. 164-177.

Irwin, J. and Jolly, V.H. (1970). Seasonal and areal temperature variation in Lake Wakatipu. ***N.Z. J. Marine and Freshwater Research*** 4, pp. 210-216.

Nairn, I.A. (1989). Geology of Mount Tarawera, Geological Map of New Zealand, 1:50 000, Sheet V16 AC, New Zealand Geological Survey, D.S.I.R., Lower Hutt, New Zealand.

Scott, B (1992). ***Waimangu a volcanic encounter.*** Waimangu Volcanic Valley.

Sheppard, D.S. (1986). Fluid chemistry of the Waimangu Geothermal System. ***Geothermics*** 15,pp. 309-328.

Whiteford, P.C. (1992a). Heat flow in the sediments of Lake Rotorua. *Geothermics,* vol. 21, pp. 75-88.

Whiteford, P.C. (1992b). Evidence for geothermal areas beneath Lake Taupo from heat flow measurements. ***Proc. N.Z. Geothermal Workshop 1992,*** Centre for Continuing Education, University of Auckland, pp 185-188.

Whiteford, P.C., Henyey, T.L. and Lee, T.C. (1992). ***Heat flow measurements in** Lakes **Wakatipu, Manapouri** and **Te Anau** and Doubtful **Sound, New** Zealand.* Geophysics Division DSIR Research Report No. 212.

Whiteford, P.C. and Graham, D.J. (1994). Heat flow in the sediments of Lake Rotomahana, New Zealand. ***Geothermics, Special Issue,*** In Press.