THE HEAT OUTPUT OF THE WAIMANGU, WAIOTAPU-WAIKITE AND REPOROA GEOTHERMAL SYSTEMS (NZ): DO CHLORIDE FLUXES PROVIDE AN ACCURATE MEASURE?

H.M. BIBBY[1], R.B. GLOVER[2] AND P.C. WHITEFORD[1]

[1] Kelburn Research Centre, IGNS, Wellington, NZ
[2] Wairakei Research Centre, IGNS, Taupo, NZ

ABSTRACT - Geothermal waters from the Waimangu, Waiotapu-Waikite and Reporoa geothermal systems find their way into three separate watersheds. The heat flow data from each of these drainage areas have been assessed making it possible to compare the heat outputs from two independent methods: direct heat measurements and the chloride flux method. For both the Waiotapu/Reporoa Valley drainage and the Waikite drainage a discrepancy exists between the two assessments, with the heat output observed at the surface (Waiotapu - 540±110 MW; Waikite - 80 MW) nearly double of that calculated from the chloride flux (300 MW; 36 MW respectively). It appears that much of the throughput of chloride does not reach the surface within the area which was monitored and the basic assumption on which the method is based has been violated. For Waimangu the direct heat output is assessed as 510±60 MW. However the ratio of enthalpy to chloride concentration of the source fluid is not well determined. Depending on the ratio chosen the heat output could lie between 360 and 800 MW. Although the chloride flux is accurately known, the heat output cannot be measured accurately without well determined data on the source fluid at depth.

INTRODUCTION

The 1994-95 year has seen the conclusion of a series of studies of the Waimangu, Waiotapu-Waikite and Reporoa Geothermal Systems. In this paper we bring together in summary form the results of a variety of heat flow assessments for these geothermal systems, made over the years and culminating with the recently completed programme of intensive study of these systems (Hunt and Glover 1994). At the commencement of the recent work, there was little agreement about the nature of the geothermal systems or their heat output - in fact, there was no agreement on the number of active and independent systems within the region. It now has been established that the springs at Waikite and Waiotapu, previously believed to be independent geothermal systems, are outputs from the same deep geothermal plume (Bibby et al. 1994, Stewart 1994). Similarly, the question of the source of the geothermal waters at Reporoa has led to a consensus that Reporoa is an independent geothermal system. These factors in turn influence the way the assessment of the heat data is interpreted.

The determination of the heat output of the springs has not been without controversy. Summing the natural heat output from each feature gave a total heat flow that was at odds with that calculated from the chloride output of the Waiotapu Valley. This difference has not been completely resolved. Prior to these studies there had been little or no assessment of the Waimangu heat flow. The recent work in Lake Rotomahana (Whiteford and Bibby, 1995) makes it possible to compare the two different techniques of heat assessment and, in this area, agreement is possible.

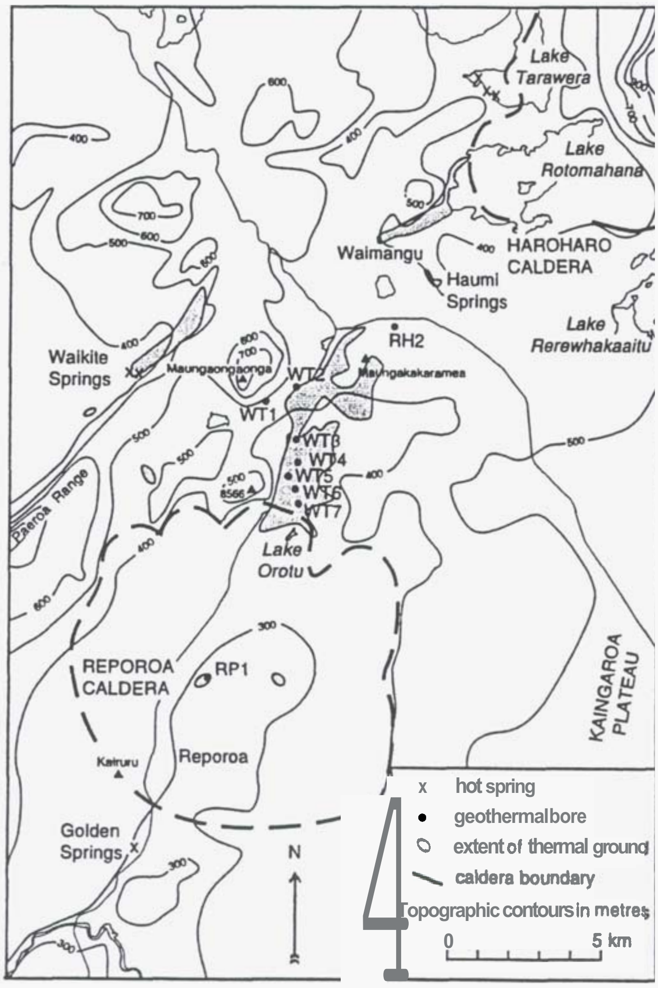

Fig. 1. Topography of the Waiotapu-Reporoa, Waikite and Waimangu areas, showing the extent of thermal features.

PHYSICAL SETTING

Waimangu, Waiotapu and Reporoa geothermal areas lie in a north-north-east trending depression, between the Kaingaroa Plateau to the east and the Paeroa Range to the west (Fig. 1). Two major calderas have been identified within this depression. To the north-east, the Haroharo Caldera lies in the vicinity of Lakes Tarawera and Rotomahana (Nairn, 1989) and includes Mt Tarawera, the centre of the 1886 eruption (Fig. 1). To the south-west, the Reporoa Caldera (Nairn et al., 1994) is the source region of the 240±50 ka Kaingaroa Ignimbrite. Between the two calderas, a topographic high near the dacite dome of Maungakakaramea marks the watershed between drainage northward into the Tarawera River, and southward to the Waikato River (see Fig. 1). The Waikite geothermal features lie further to the west, at the foot of the Paeroa scarp, which marks the western edge of the Paeroa Range. Details of the geological structure are given in Wood (1994).

Geothermal fluids discharged at the surface can join one of the three distinct surface drainage systems. To the west

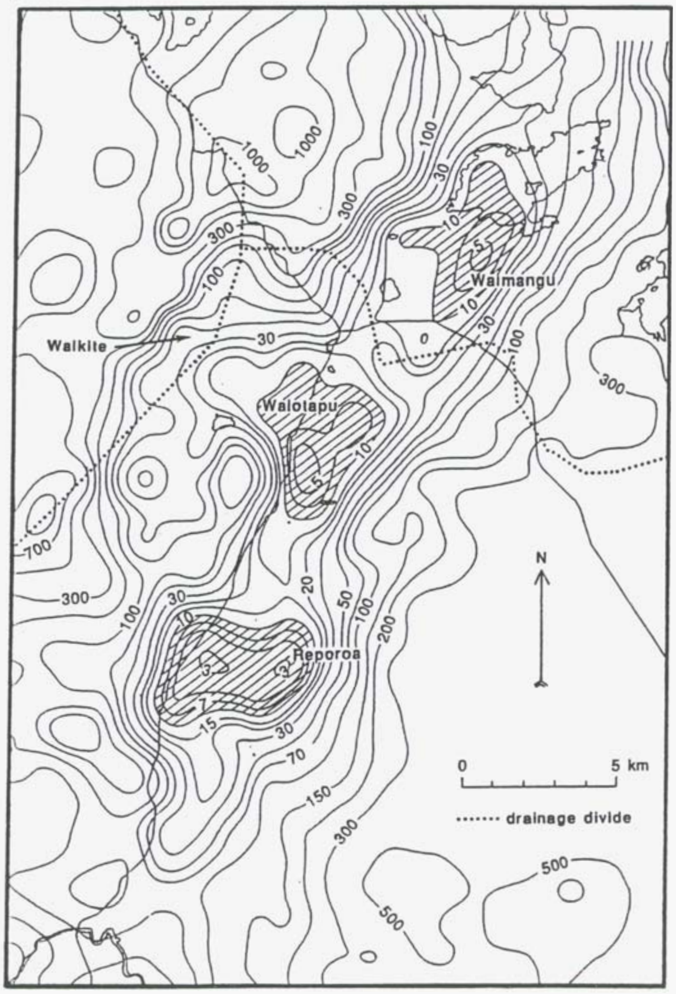

Fig. 2. Contours of apparent resistivity showing the three major low resistivity regions (AB/2 = 500m, from Bibby et al. 1994). Also shown are the approximate locations of the drainage divides. Note that the Waikite springs, although forming part of the Waiotapu geothennal system, lie within a separate drainage system).

(Fig. 2) the Paeroa scarp acts as a drainage divide, separating the Waiotapu Valley from the Ngakuru graben. Thus, waters discharged at the Waikite and Puakohurea Springs eventually find their way into the Whirinaki arm of Lake Ohakuri on the Waikato River. Between Waiotapu and Waimangu a second drainage divide (Fig. 2) separates surface waters which either flow northward to (eventually) reach Lake Tarawera and Tarawera River or southward to the Waiotapu Stream and thence to the Waikato River. Thus geothermal waters, upon reaching the surface, can take one of three possible paths to the major river systems.

MEASUREMENT TECHNIQUES

A variety of techniques have been applied to determining the natural heat output of the geothermal fields of the Taupo Volcanic Zone. Early assessments were based on summation of the heat output by way of fluid flow, conduction and evaporation from individual thermal features. Some of these assessments are unreliable, particularly the estimation of evaporative heat transfer. Very few detailed assessments of thermal losses have been made since Allis (1980) assessed changes in the heat flow at Wairakei due to exploitation.

The use of chloride fluxes to estimate geothermal heat output (Ellis and Wilson, 1955) is now widely used in New Zealand (e.g. Bibby et al., 1984; Finlayson and Nairn, 1981; Glover, 1992). This method is based on the principle of conservation of chloride ions within geothennal flows. The rate at which chloride is added to the rivers draining any geothermal field (above the background level) is equated to the total chloride flux flowing from depth within the upflow zone of the geothermal field. Hence, if the ratio of enthalpy to chloride concentration (Q/Cl) is known for the deep geothermal fluid (single liquid phase), the chloride flux can be used to estimate the rate of energy transport from depth. Such a heat-flow estimate assumes that all the chloride in the upflowing geothermal water is discharged into the surface drainage system. The uncertainty in the chloride-flux method results from difficulties in obtaining accurate estimates of Q/Cl for the source fluid. Where drill hole samples are available, estimates can be made of temperature and chemistry of the source fluid. Although Q/Cl appear to be constant within most geothermal fields, large differences occur between fields. In the TVZ, estimates of Q/Cl range from 0.45 MJ/g at Tokaanu (based on Robinson and Sheppard, 1986) to 2.7 MJ/g at Rotokawa (Krupp et al., 1986) and Orakei Korako. The only field where a single value of Q/Cl may not be applicable is Ohaaki, where ratios are 1.4 and 1.1 MJ/g, have been suggested for the east and west sectors, respectively (Hedenquist, 1983).

When a region is covered by the waters of a lake, a third technique is available. By using the lake waters as a calorimeter and accurately assessing the change in temperature of the lake waters and the output of heat from the lake, it is possible to make an indirect measure of the heat input through the lake floor. All three techniques have been used in this study.

HEAT FLOW ESTIMATES

Waiotapu Valley

The thermal features of the Waiotapu geothermal area were studied in detail as part of the early geothermal assessment (DSIR, 1957, 1963). As part of these detailed investigations an assessment was made of the total heat output of all the mapped thermal features. Benseman et al. (1963) give area by area summations of the heat output from all the thermal features east of the Paeroa scarp by way of water discharge, evaporation from water surfaces and through surface heat losses from hot ground. Including the Mangaongaonga fumaroles (20 MW, Lloyd, 1963) the total heat output was estimated to be 560 MW. This figure excludes any natural heat output from the Reporoa area, although it does include an assessment of 80 MW for Maungakakaramea, half of which could arguably be associated with the drainage north to the Waimangu catchment. Of this, the greatest contribution is from the evaporation losses (68%), while only 8% is in the form of water discharge. Thus, the estimate is very sensitive to the method of calculation of evaporative losses. The other components of the heat flux will be more reliable, being supported by ground temperature survey data which covered much of the area of thermal features. The total (520 MW) is similar to an earlier estimate (410 MW) made by Healy (quoted in Grange 1955).

Also lying within the Waiotapu Valley, the Reporoa geothermal area lies about 5 km south of the Waiotapu area and consists of two small areas of thermal ground (Fig. 2). At the time of Benseman's heat flow measurements, the thermal features at Reporoa were regarded as an out flow from the Waiotapu geothermal system (Healy and Hochstein, 1973) and no independent assessment was made of these features. In addition to the thermal features that occur within the resistivity anomaly at Reporoa, two further lower temperature springs can also be linked to the Reporoa geothermal system. Five kilometres to the south are the Golden Springs, which are characterised by a very high flow rate (49 l/s) of warm water (40"-50°C)(Mongillo and Clelland, 1984); and Butcher's Pool, with a flow of 5 l/s. The total heat output from the Reporoa area is 10 to 20 MW.

There are several estimates of the chloride flux passing out of the Waiotapu Valley. Newson (1993) measured a chloride flux of 258 g/s in the Waiotapu Stream at Reporoa. Additional data, covering an overlapping time span, can be derived from a long term waterquality study (Timperley and Huser, 1994). They give a total chloride flux of 225 g/s for the same portion of the Waiotapu Valley, of which the non-geothermal contribution was estimated to be 11 g/s. Unfortunately, Timperley and Huser (1994) were unable to obtain a reliable measurement at the lowest point in the stream, relying instead on the summation of the known inputs. Giggenbach et al. (1994) give a further estimate, based on data collected in 1978, of 241 g/s for the upper part of the valley (ending just below the Waiotapu thermal features). None of these include full assessments for input south of Reporoa although the chloride flux from Golden Springs adds only about 2 g/s (Newson 1993, Timperley and Huser 1994). A less precise estimate of the anomalous chloride for the same drainage (290±100 g/s), determined from the change in chloride flux along the Waikato River (Hochstein et al., 1992), is in reasonable agreement with the other measurements.

Analysis of the waters encountered in the drillholes at Waiotapu (Hedenquist and Browne, 1989) suggests a deep, parent-water of 300°C and 1100 mg/kg chloride yielding a value for Q/Cl of 1.22 MJ/g. Giggenbach et al. (1994) give a possible parent water with the corresponding ratio of 0.91 MJ/g. Thus the heat flow suggested by the chloride fluxes given above range between 195 MW and 300 MW. Clearly a large discrepancy exists between the heat flux derived from the two different techniques. It is difficult to reconcile these data as the heat output derived from the chloride fluxes is at most only a half that of the direct heat measurement and approximately equal to Benseman's (1963) data without any evaporative component. This is discussed in more detail in a later section.

Waikite Valley

The Waikite thermal area comprises a series of springs (Waikite Springs, Puakohurea Springs) which form a lineation along the foot of the Paeroa fault scarp. A smaller area of hydrothermally altered ground and gas discharge lies about 3 km south of the Waikite springs at about 100 m higher elevation. The springs are described in detail in Glover et al. (1992). All the features lie on or near Otamakokore Stream allowing both chloride flux and direct heat in the flow to be measured. The thermal features are derived fkom the same source fluids at depth as those at Waiotapu (Stewart, 1994) although at Waikite they have been diluted, resulting in comparatively low chloride concentrations.

Several estimates have been made of the total heat discharge in the Waikite Valley. Healy (1952) gave mass flow and temperature data for the Otamakokore Stream that drains the Waikite area, which is equivalent to a heat flow (above 12°C) of 40 MW. Data from early in 1992 gave a similar value (43 MW, Glover et al. 1992). These figures exclude conductive and evaporative heat losses from the springs and fumaroles and from the stream water above the gauging site. Healy made an estimate of the heat discharged from the "Main Waikite Spring", the "Middle Group" and the "Northern Group" totalling 81 MW.

The chloride flux from Waikite measured in the Otamakokore Stream was 30 g/s (Glover et al. 1992). Thus, from Healy's figures, the value of Q/Cl for the Otamakokore Stream is 2.7 MJ/g. Waikite Springs, the thermal feature with both the highest temperature (99.5 "C) and the highest chloride concentration (145 mg/kg), gives a similar ratio of 2.87 MJ/g. If the fluids are assumed to have the same deep source as the discharge at Waiotapu, we would expect that the Q/Cl ratio for the deep fluid to be that of the deep Waiotapu fluids, ie 1.22 MJ/g. This highlights the same apparent discrepancy between the heat and chloride fluxes as seen at Waiotapu. It is noteworthy however that applying the value of Q/Cl obtained fkom surface measurements at Waikite to the Waiotapu area, would give 580 MW, in close agreement with the directly measured heat output.

Waimangu

The hydrothermal system at Waimangu underwent a massive disruption as a result of the Tarawera eruption of June 10, 1886. Powerful hydro-volcanic explosions destroyed the pre-1886 thermal features and formed the modem Lake Rotomahana. Spectacular geysering and violent hydrothermal eruptions occurred in the early 1900s (Keam, 1988; Simmons et al., 1993). This activity has now waned, with the present day Waimangu thermal features mainly occurring along the Waimangu Valley, and at the 'Steaming Cliffs' along the western shore of Lake Rotomahana (Nairn, 1979; Simmons et al., 1993). Smaller discharges also occur at the Haumi Springs to the south of the main features in the Waimangu Valley and at a number of hot springs and seeps along the southern shores of Lake Tarawera.

All surface discharge drains directly into Lake Rotomahana to the north of the Waimangu Valley. In addition to the surface discharge, geothermal fluids are observed to enter through the floor of Lake Rotomahana (Naim 1989; Whiteford and Graham, 1994). Prior to 1886 the former Lake Rotomahana drained northward into Lake Tarawera. This surface flow was cut off by debris from the 1886 eruption and the present Lake Rotomahana has no surface outlet. However, both the volume and chloride concentrations of the lake water are inconsistent with removal of fluid by evaporation alone. Subsurface drainage must take place northward into Lake Tarawera. Indeed the warm springs found along the southern shores of Lake Tarawera probably have their origin in the Waimangu area. Thus, the entire output from the northern drainage (Waimangu) eventually finds its way into Lake Tarawera and the Tarawera River.

The surface heat flux and that through the floor of Lake Rotomahana have been assessed separately. The thermal discharge from the two largest features in Waimangu Valley (Frying Pan Lake and Inferno Crater Lake) is given by Scott (1992) as 150 MW (note that the figures by Scott are incorrectly given as output per year instead of per day – Brad Scott, pers. comm. 1993). An earlier measurement of 180 MW for the heat output of the same features (attributed to R.F. Keam) is given by Nairn (1981). No measurement has been made of the output of the other smaller features in the Waimangu Valley, although an estimate of 80 MW is given by Naim (1981), 10 MW of which is attributed to the Haumi features. Similarly, no measurements have been made of the heat output from the Steaming Cliffs nor of the input into the shallow waters of Lake Rotomahana. Although Nairn (1981) estimated 100 MW from these features, we include a more conservative value of 50 MW. Together the total is 280 MW to 310 MW. To this must be added the input into the deep part of Rotomahana and that part of the Waiotapu system that lies to the north side of the drainage divide (approximately 40 MW was assumed in the Waiotapu assessment).

Lake heat output: A detailed survey of both lake temperature and lake bottom temperature gradient has been made by Whiteford and Graham (1994). The locations of these measurements and contours of the measured gradients are shown in Fig. 3. Using these data the conductive heat input into the lake was calculated to be 19 MW. In addition to the conductive heat into the lake the survey also showed the existence of several areas of localised high temperatures, which are believed to be sites at which geothermal waters enter the lake from below. This convective input to the lake is considerably larger than the conductive flow.

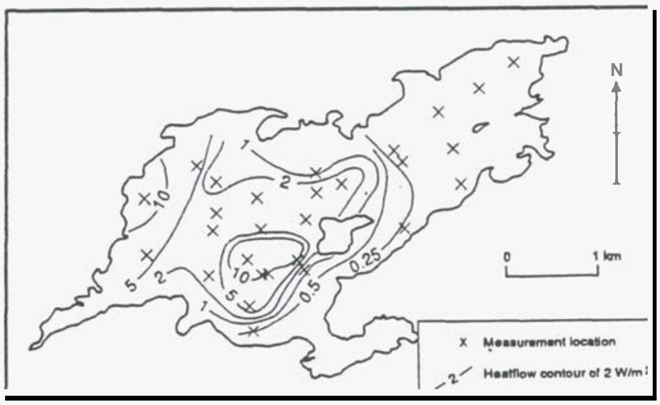

Fig. 3. Contours of the temperature gradients (in W/m²) measured in Lake Rotomahana. Measurement sites are shown by crosses.

Over the period of observation, it was noticed that the bottom water temperatures appear to increase gradually by about 0.1°C (measurement resolution is 0.001°C). Such a systematic increase in temperature throughout the lake results from both the conductive and convective heat transfer into the lake waters. Quantifying this change thus provides a means of estimating the total heat output through the lake floor. Whiteford and Bibby (1995) analysed the bottom water temperatures to separate variations with position, depth and time. Results of this analysis are shown in Table 1. Some variation of bottom water temperature with position is observed, but the parameter that is clearly most significant is the increase in temperature with time - viz. 0.011 ± 0.003°C/day or 90 ± 25 days/°C. This change is shown in Fig. 4.

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	fo.02
χ	"——	-0.2	±0.5
E	°C/day	0.011	±0.003

Within Lake Rotomahana, as with other lakes of the TVZ, there is a distinct thermocline or stable layer of warm water at the surface of the lake. The water beneath the thermocline is essentially isolated from the thermocline. Heat transfer between the two bodies occurs by conduction but is a slow process and little heat is transferred. Although streams containing thermal water discharge from Waimangu into Lake Rotomahana, the temperatures of these discharges are higher than that of the lake water beneath the thermocline. Hence the discharge waters do not sink through the thermocline but add to it, and give rise to the unusually deep thermocline observed at Lake Rotomahana. Whiteford and Bibby (1995) estimate that the transfer of heat across the thermocline will contribute at most 0.001°C/day, which is small compared with the observed heating at Rotomahana and can be neglected. Hence the only significant heat input into the waters beneath the thermocline is from the thermal areas in the bottom of the lake.

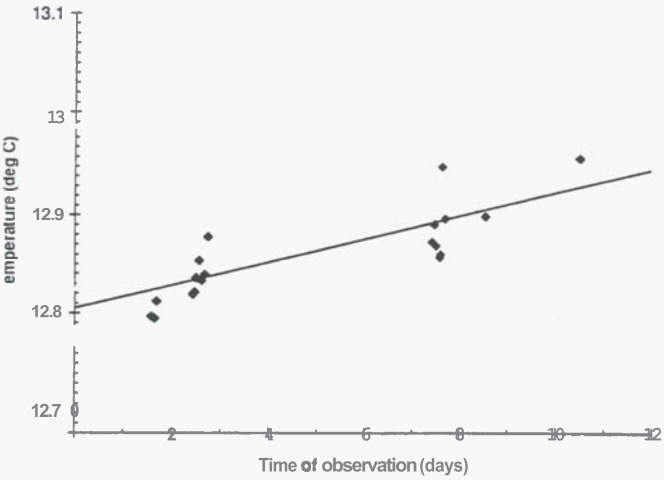

Fig. 4. Variation of bottom water temperature with time at Lake Rotomahana together the line of best fit. Note that the small variation with location has been removed.

The rate of 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 beneath the thermocline was estimated to be 0.32 km^3. Using the observed rate of increase in temperature, the energy input (both conductive and convective) from the lake floor is estimated to be 175±45 MW.

Adding all the components of the heat output gives a total output of Waimangu area as 510±60 MW.

Chloride flux.
As the total flow of geothermal waters from Waimangu finds 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 an anomalous chloride flux at the outlet of Lake Tarawera of 420 g/s (after removal of a non-geothermal component of 6 ppm). This was independently assessed one of the authors (R.B. G) in 1987 when an anomalous flux of 410 g/s was measured.

The ratio of enthalpy to chloride concentration for the deep waters of Waimangu has been estimated by several authors, although all are based on the surface discharge in the Waimangu Valley. No samples are available for the geothermal waters discharged into the bottom of Lake Rotomahana nor are drill hole samples available. Water from either of these deeper sources would provide a better sample of the deep waters. Finlayson and Nairn (1981) converted the chloride flux to heat flow using a value of Q/Cl of 0.86 MJ/g, a medium value for the TVZ as a whole. From the spring chemistry, Sheppard (1986) suggests a 'parent' water containing 725 mg/kg chloride at temperature of 258°C, and Simmons et al. (1994) suggests 585 mg/kg chloride at 260 °C which give values for Q/Cl of 1.55 and 1.94 MJ/g respectively. Without a knowledge of the chemistry of the deep waters entering through the floor of Lake Rotomahana there must be considerable uncertainty in any estimate, and these must be regarded as upper bounds. Taking the ratio from Sheppard (1986) gives a total heat output of 635 MW, with the other estimates giving 360 MW (Finlayson and Nairn, 1981) and 795 MW (Simmons et al. 1994). Given that the ratios derived from the Waimangu Valley are likely to be upper bounds, the total heat output is in reasonable agreement with that measured directly. However the possible range is very large.

Table 2. *Heatflow and chloride fluxes from the Waiotapu, Waikite, Reporoa and Waimangu areas. Alternative estimates are shown in parenthesis.*

	Waiotapu & Reporoa	*Waikite*	*Waimangu*
Measured heat (MW)	540±110	80	510±60
Chloride flux (g/s)	247 (214)	30	420
Q/Cl (MJ/g)	1.22 (0.91)	1.22 (2.87)	1.55 (0.86-1.94)
Heat from Cl (MW)	300 (195)	36 (86)	635 (360-795)

DISCUSSION AND CONCLUSION

The total heat flow from each of the areas is summarised in Table 2.

Despite the wealth of new measurements and data obtained during the recent study of these three geothermal areas, there remains some unresolved problems. The use of chloride fluxes to calculate the heat output of geothermal systems has now become well established. However there are few examples of geothermal systems where sufficient data is available to allow a direct comparison of total heat output as measured by direct surface heat measurements with that estimated from chloride flux. The Waiotapu, Waikite and Waimangu areas provide three examples where such comparisons can be made and together they highlight the problems that can arise.

None of these areas show a good agreement between the two independent estimates although the reasons for the difference vary from area to area. In the Waimangu area, the heat output is high, and measurements have all been made in recent years with modem instrumentation. As a consequence the direct heat output is known with greater accuracy than is associated with the older data in the other areas. However, the greatest unknown in this case is the ratio of enthalpy to chloride concentration where various estimates differ by over 100%. With no deep sampling available and surface springs containing a large proportion of steam heating, it is difficult to provide an appropriate ratio with any accuracy at all. As a consequence, although the chloride flux can be determined with some certainty, the heat flow associated with this flux cannot be ascertained with accuracy. The possible range of values is too great for this to be regarded as a test of the validity of the tacit assumptions made in applying chloride flux methods.

At Waiotapu and Waikite a more fundamental difference between the methods is apparent and there is a very large discrepancy between the heat output measured directly and that estimated from the chloride flux. The original measurements of the heat output of individual features at Waiotapu were made before 1957 and there is some doubt as to the accuracy. Benseman et al. (1963) suggest accuracy to within 20%. It is unlikely, however, that the total is out by a factor of two which would be necessary to match the heat flow derived from the chloride flux. Nor is it likely that there have been substantial changes in the heat flow between the different surveys. Indeed a measure of the chloride flux from data measured in 1978 (Giggenbach, 1994) agrees very well with that of 1995. Furthermore the same discrepancy between the two heat flow measures occurs at Waikite where the data has much less uncertainty.

A close look at the ratio of entalpy to chloride concentration suggests a possible explanation. The ratio determined for the deep fluids as seen in the drillholes is quite different from that of the thermal features. Such a difference is typical where a substantial amount of heat is transferred by conduction or by steam such as Waiotapu. The chloride that does not make it to the surface in the immediate vicinity of the thermal features is assumed to eventually make its way into the normal surface drainage. Certainly most of the geothermal waters seen at Waiotapu find their way to the surface by way of seeps rather than as well defined springs. Thus it seems likely that not all the chloride find its way into the surface drainage within the area the measurements were made. Subsurface flows could easily transport chloride waters out of the area. Nor does such a subsurface movement have to be horizontal. A basic assumption of the chloride flux method is that the geothermal systems are 'once through' ie all of the geothennal waters discharge at the surface, with no recirculation. The geology of the Waiotapu suggests that, unlike the majority of geothermal systems in the TVZ, old (less permeable) ignimbrites are found very close to the surface. Such geology could encourage the dissipation of heat from the deeper fluids by boiling and conduction over a large area, with a portion of the cooled saline fluids joining the downflow of meteoric waters between the geothermal fields. Thus it seems possible that the basic assumption of the chloride flux method may have been violated in this instance.

ACKNOWLEGEMENTS

This work was funded by the New Zealand Foundation for Research, Science and Technology. Institute of Geological & Nuclear Sciences contribution number 685.

REFERENCES

Allis, R.G., 1980. Changes in heat flow associated with exploitation of Wairakei geothennal field, New Zealand. *New Zealand* Journal *of Geology and Geophysics,* **24:1-19.**

Benseman, R.F., Fisher, R.G. and Dickinson D.J. 1963. Survey of surface heat output at Waiotapu. In Waiotapu geothermal field. DSIR Bulletin 155. Wellington. 50-58.

Bibby, H.M., Dawson, G.B., Rayner, H.H., Stagpoole, V.M. and Graham, D.J., 1984. The structure of Mokai geothermal field based on geophysical observations: *J. Volcan. Geothenn. Res.* **20:** 1-20.

Bibby, H.M., Stagpoole, V.M. Bennie, S.L. and Caldwell, T.G., 1994. Resistivity structure of the Waimangu, Waiotapu, Waikite and Reporoa geothermal areas, New Zealand. *Geothennics.* **23:445-473.**

DSIR, 1957. The Waiotapu Geothermal Field. *Geothermal Report No. 3.* NZ DSIR, Wellington. 119 pp.

DSIR, 1963. Waiotapu Geothermal Field. *Bulletin 155.* NZ DSIR, Wellington. 142pp.

Ellis, A.J. and Wilson, S.H., 1955. The heat from the Wairakei-Taupo thermal region calculated from the chloride output. *New Zealand Journal of Science and Technology,* **36:622-631.**

Finlayson, J.B. and Nairn, I.A., 1981. Chloride flux measurements in the Tarawera River system. Department of Scientific and Industrial Research. *Geothermal Circular JBF2, IAN3.* DSIR, Wellington.

Giggenbach W.F., Sheppard D.S., Robinson B.W., Stewart M.K. and Lyons G.L., 1994. Geochemical structure and position of the Waiotapu geothermal field, New Zealand. *Geothennics* **23:599-644.**

Glover R.B., 1992. Integrated heat and mass discharges from the Rotorua geothermal system. *Geothennics* **21:89-96.**

Glover, R.B., Klyen, L.E. and Crump, M.E., 1992. Spring chemistry of the Waikite-Puakohurea thermal area. *Proc. 14th N.Z. Geothermal Workshop 1992,* 63-72.

Grange, L.I., 1955. Geothermal steam for power in New Zealand *Bulletin 117, DSIR,* Wellington, 102pp.

Hedenquist, J.W., 1983. Characteristics of Broadlands-Ohaaki water chemistry and changes subsequent to initial production *Proceedings of the 5th New Zealand Geothermal Workshop,* 151-156. University of Auckland.

Hedenquist, J.W. and Browne, P.R.L., 1989. The evolution of the Waiotapu geothermal system, New Zealand, based on the chemical and isotopic composition of its fluids, minerals and rocks. *Geochim. Cosmochim. Acta* **53:2235-2257.**

Healy, J., 1952. Waikite Hot Springs - to inspect the Waikite thermal area and assess its geothermal resources. *DSIR Report,* November 1952. Rotorua.

Healy, J. and Hochstein, M.P., 1973. Horizontal flow in hydrothermal systems. *J. Hydrology* **12:71-82.**

Hochstein, M.P., Simmons, S.F., Maggs, G.R. and Newson, J., 1992. Assessment of thermal water input into the Waikato River - results of a test study. *Proc. 14th Geothermal Workshop 1992,* 51-56. University of Auckland.

Hunt T.M. and Glover R.B., 1994. Waimangu, Waiotapu and Waikite Geothermal Systems, New Zealand. *Special issue Geothennics* **23(5/6).**

Keam, R.F., 1988. Tarawera. R.F. Keam (publ.) Auckland, New Zealand. 472 pp.

Krupp, R., Browne, P.R.L., Henley, R.W. and Seward, T.M., 1986. Rotokawa Geothermal Field. *In:* Henley, R.W., Hedenquist, J.W., and Roberts P.J. *(editors)* Guide to the active epithermal (geothermal) systems and precious metal deposits of New Zealand. *Monograph series on Mineral Deposits* **26:47-55.** Gebruder Borntraeger, Berlin.

Lloyd E.F., 1963. Thermal activity at Waiotapu. *In* Waiotapu geothermal field. *DSIR Bulletin 155.* Wellington. p42-49.

Mongillo, M.A. and Clelland, L., 1984. Concise listing of information on the thermal areas and thermal springs of New Zealand. *DSIR Geothennal Report No. 9.* DSIR, Wellington. 228pp.

Nairn, I.A., 1979. Rotomahana-Waimangu eruption 1886: base surge and basalt magma. *N.Z. J. Geol. Geophys.* **22:263-374.**

Nairn, I.A., 1981. Geothermal resources of the Okataina Volcanic Centre. *Geothermal Circular IAN2.* DSIR, Wellington.

Nairn, I.A., 1989. Geological map of New Zealand: 1:50 000, Sheet U16, AC. Mount Tarawera. DSIR, Wellington.

Nairn, I.A., Wood, P.C. and Bailey, R.A., 1994. The Reporoa Caldera, Taupo Volcanic Zone: source of the Kaingaroa ignimbrites. *Bulletin of Volcanology.* **56:529-537.**

Newson, J., 1993. Geothermal and groundwater hydrology of the Reporoa-Waiotapu basin. M Phil thesis, Auckland University. 116pp.

Robinson, B.W. and Sheppard, D.S., 1986. A chemical and isotopic study of the Tokaanu-Waihi Geothermal area. *Journal of Volcanology and Geothermal Research, 27:*135-151.

Scott, B.J., 1992. Calorimetry and hydrothermal eruptions, Waimangu hydrothermal field, 1971-1990. *Proc. 14th N.Z. Geothermal Workshop 1992,* .247-252. University of Auckland.

Sheppard D.S., 1986. Fluid chemistry of the Waimangu geothermal system. *Geothennics* **15:309-328.**

Simmons S.F., Stewart M.K., Robinson B.W. and Glover R.B., 1994, The chemical and isotopic compositions of thermal waters at Waimangu, New Zealand. *Geothennics* **23:539-554.**

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

Stewart M.K., 1994. Groundwater contributions to Waikite geothennal fluids. *Proceedings of 16th New Zealand Geothennal Workshop 1994.* 109-114. Auckland University.

Timperley M.H. and Huser B.A., 1994. Natural geothermal inflows to the Waikato River. *Proceedings of the 16th New Zealand Geothermal Workshop 1994. 57-64.* Auckland University.

Whiteford, P.C. and Graham, D.J., 1994. Heat flow measurements in Lake Rotomahana, New Zealand. *Geothennics* **23:527-538.**

Whiteford, P.C. and Bibby, H.M., 1995. The heat discharge into Lake Rotomahana, North Island, New Zealand. *Proc. World Geothermal Congress 1995,* 757-562.

Wood, C.P., 1994. Aspects of the geology of Waimangu, Waiotapu, Waikite and Reporoa geothermal area, Taupo Volcanic Zone, New Zealand. *Geothennics.* **23:401-422.**