ASSESSMENT OF HEAT LOSSES OF STEAMING GROUND BY CALORIMETRY

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SUMMARY – The total heat flux at steaming ground sites was measured using a water-filled ground calorimeter; the flux varies between c. 0.03 and 2.3 kW/ m^2 at sites where boiling temperatures occur at depths of c. 4 m and 0.1 m respectively. Analysis of various soil parameters and temperature logs points to a 'heat pipe' transfer mechanism. This maintains a high conductive transfer in a thin surface layer. In addition, convective transfer of ascending vapour through the surface layer increases the total flux.

1. INTRODUCTION

Monitoring of the thermal regime at Karapiti (Wairakei Field, NZ) has shown that heat transfers to the surface by conductive and convective components whose proportions vary with the gradient of soil temperatures and soil properties at shallow depth. An analysis of the physical properties of soil samples, together with estimates of their thermal difisivity, allows an assessment of the thermal conductivity, k. Using values of the appropriate near-surface temperature gradient ($\Delta T/\Delta z$), representative values of the conductive heat loss (Q-cond) can be obtained (Bromley and Hochstein, 2001).

The convective loss component (Q-conv), associated with the diffuse ascent of vapour-through the near-surface layer, cannot be measured directly, but can be obtained by measuring the total heat flux (Q-tot) at the surface since:

$$\text{Q-conv} = (\text{Q-tot} - \text{Q-cond}), \quad (\text{unit: } W/m^2). \quad (1)$$

2. EARLIER CALORIMETRY STUDIES

Calorimetry has been used in the past to assess Q-tot of steaming ground areas. The first attempt to measure the total heat flux at the surface of steaming ground in New Zealand geothermal prospects was that by Benseman (1959a). A ground calorimeter with an open bottom was used with ambient air being passed over the hot ground. Total flux values between 0.04 and 2 kW/m^2 were obtained. The data showed a large scatter when plotted versus ground temperature (between 30 and 100 deg C respectively) at 0.35 m depth.

The Benseman calorimeter was also used together with a disk of known conductivity (modified Lees' disk) to obtain additional information about the total losses from the Karapiti area (Wairakei Field). The two methods produced scattered data within the range of 0.03 to 0.3 kW/m^2 when plotted versus soil temperatures at 0.15 m depth (Thompson et al., 1964). Bare, steaming ground with visible discharge of steam was assessed using a steam-collecting dome (Thompson et al., 1964; Dawson, 1964). Calorimeter studies of steaming ground in NZ were discontinued after 1965.

A ground calorimeter with an open bottom, similar to that of Benseman, was also used by Le Guern et al. (1980) to assess the heat flux of fumarolic ground in Italy. Dry air was used as fluid; the observed fluxes showed less scatter' and were within the range of c. 0.4 and c. 4 kW/m^2 for near-surface soil temperatures between 25 to 100 deg C respectively. Their assessment of conductive losses without measuring the thermal conductivity of the soils, however, is open to criticism.

Since soil temperatures of hot and steaming ground (at a given reference depth) control plant growth, order of magnitude heat fluxes can be assigned to areas with similar types of stressed vegetation if sufficient representative flux data are available. The concept was introduced by Benseman (1959b). The empirical classification of nine types of steaming ground by Dawson (1964) was reduced to three types by Allis (1979).

Although infrared measurements allow a good definition of the surface areas of hot and steaming ground with elevated surface temperatures, the simplified classification of Allis was used until recently to assess local heat losses in NZ, since representative data allowing quantitative interpretation of IR-data over steaming ground were not available (Bromley and Hochstein, 2000).

3. CONSTRUCTION OF A CALORIMETER SUITABLE FOR STEAMING GROUND

To obtain representative heat flux values for steaming ground, a new ground calorimeter was built. Although a calorimeter with an open bottom is, in principle, well suited for heat flow studies of steaming ground, the low heat capacity of air, problems in monitoring the variable moisture content of a ground hugging air flow, and the poor reproducibility of the older 'air calorimeter' measurements cited above, led us to construct a closed calorimeter. This uses water with its high heat capacity as the transfer medium.

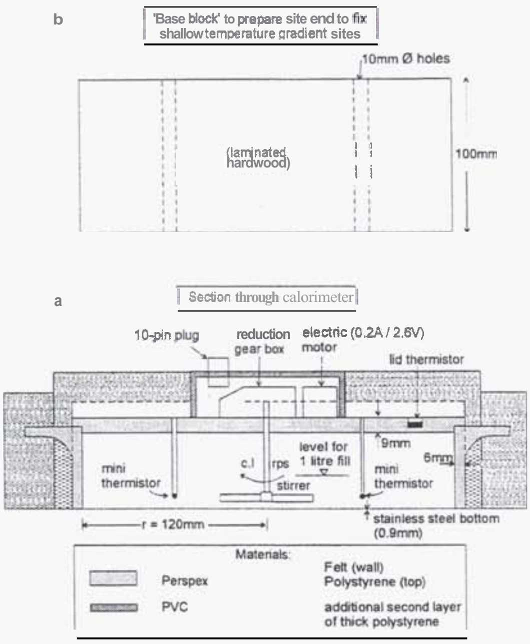

Figure 1: a) Section through ground calorimeter usedinthis study. b) 'Base block' used to prepare sites in the field.

The calorimeter design is shown in Fig.1a. To minimise losses at the base, we used a thin (0.9 mrn) stainless steel plate and perspex of lew thermal conductivity (0.18 W/mK) for the mantle and the lid. Three mini-thermistors of high impedance and small thermal capacity were used as temperature sensors with a fourth thermistor monitoring the lid temperature. A stirrer was installed to achieve good mixing of the liquid; it is driven by a small DC-motor via a reduction gearbox, which turns the propeller at c. 1 revolution per second. The stirrer is required for measurement of fluxes < 200 W/ m2; for greater fluxes the liquid is also mixed by internal convection. The heat generated by the mechanical work of the stirrer is small (c. 0.3 W) and can be neglected. To reduce conductive losses or gains through mantle and lid, an insulating double layer of polystyrene was used for the lid, and a felt-polystyrene layer for the mantle.

The calorimeter was calibrated in the laboratory under constant air temperature. It was placed on an electric heating plate with a contact area similar to that of the calorimeter bottom plate. Using a monitored AC-pulse for given heating periods, the anomalous heat of the heating plate was transferred by conduction through the bottom plate to the calorimeter. From known material constants it was estimated that the stainless steel bottom (0.34 kg) and the perspex mantle (0.28 kg) can store c. 0.27 kJ when their temperature is raised by 1 deg C (neglecting transients). The lid (0.51 kg) can also store up to 0.5 kJ when its temperature rises 1 deg C. This heat can derive, for example, from the latent heat of minor vapour ascending to the lid inside the tightly closed calorimeter when the temperature of the water in the calorimeter exceeds the lid temperature. The anomalous heat, AQ, transferred to the water in the calorimeter of mass m and specific heat c during the calibration tests is given by:

$$AQ = m\,c\,(T2 - T1) + L(b+m) + L(l) \qquad (2)$$

where T1, T2 are the mean temperatures of the liquid at the start (time t_1) and the end (time t_2) of the monitoring period. The terms L(b+m), and L(l) describe the minor heat storage components for the bottom and mantle, and the lid of the calorimeter, respectively. The calibration tests showed that the relative error of measuring AQ using the calorimeter (for (T2 -T1) < 5 deg C) is of the order of *6%.*

4. FIELD TESTS

Field tests were conducted at selected Karapiti sites during the summer and autumn of 2001/2. The thermistor data of the calorimeter were monitored with a Fluke Hydro logger initially at 30 s (later at 15 s) intervals; air temperature, and later soil temperature at 50 mm depth, were also monitored. Representative sites, as shown in Fig.2, were selected to obtain a range of fluxes.

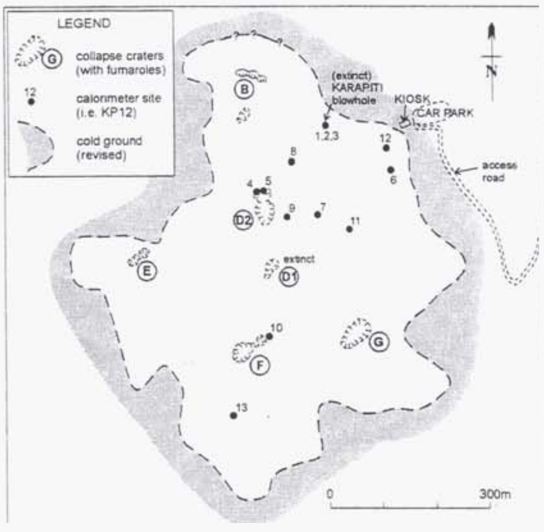

Figure 2: Map of the Karapiti steaming ground area showing location of calorimeter sites (Boundaries of cold ground taken from an air photo from 18/02/00).

These included sites KP1 to 5, previously occupied for conductive heat loss measurements (Bromley and Hochstein, 2001). We only used sites where no visible steam discharges occurred.

For good contact, each site was levelled by using a heavy wooden 'base block' (Fig.1b). Soil temperatures at 0.01, 0.05, 0.09 and 0.19 m depth were measured at 4 points coinciding with the position of holes through the block. This gives the representative temperature field beneath each calorimeter site. The thermal conductivity of the near-surface soil layer was assessed from various physical parameters of soil samples (Bromley and Hochstein, 2001) taken from depths between 0 and 0.15 m, later at 0.05 **m** intervals. The calorimeter was partly filled with water (mass of 0.5 or 1.0 kg) whose initial temperature was kept close to ambient. The small temperature difference between the water and the surrounding materials induced heating or cooling and a drift in the water temperature. An example of this is shown in Fig.3, the monitoring record at site KP10 (on 21.03.02). The temperature drift of the calorimeter was monitored for c. **8** min on top of the wooden block before and after placing the vessel on the ground and for 2 min in between the two **5** min heating periods. An assessment of the temperature drift ($\Delta Td/\Delta t$) as a function of recording time (t) was obtained by fitting a linear function to the time varying difference between lid and water temperatures.

The heat-flux, Q-tot, through the bottom of the calorimeter was computed using a time-based temperature gradient approach. Denoting the mean gradient of the steep temperature rise at time t by ($\Delta Tc/\Delta t$) and the calculated gradient of the drift by ($\Delta Td/\Delta t$), the value for Q-tot at time t is given by:

$$Q\text{-tot} = [\, m\, c\, \{(\Delta Tc/\Delta t) - (\Delta Td/\Delta t)\}\,] / a \qquad (3)$$

where m is water mass, c specific heat, and a is the area covered by the calorimeter. The uncertainty in computing the ($\Delta T/\Delta t$) values was reduced by using a least-squares, linear fit program applied to successive segments of the record.

A comparison of records from all sites indicates different heating responses. At sites with dominantly conductive heating, the drift-reduced gradient (ATclAt) - ($\Delta Td/\Delta t$) in equation (3) remained almost constant during the heating period (see Fig.3, site KP10). Such transfer only occurred at a few sites. At the other sites, convective and conductive transfers occur together, with the heating gradient in the record decreasing with time during a heating cycle. The computed value Q-tot (equation **3**) is therefore an apparent flux, usually attaining a maximum value at the beginning of each heating cycle. An example of this is the record shown in Fig.4, at site KP 13. At sites with similar characteristics, the ground was often moist at the surface at the end of the recording period; traces of condensate were also visible at the bottom of the calorimeter when it was lifted fkom these sites. Composite heating curves were also obtained where ($\Delta T/\Delta t$) gradients reached a maximum in the middle of a heating cycle (seeFig.4b).

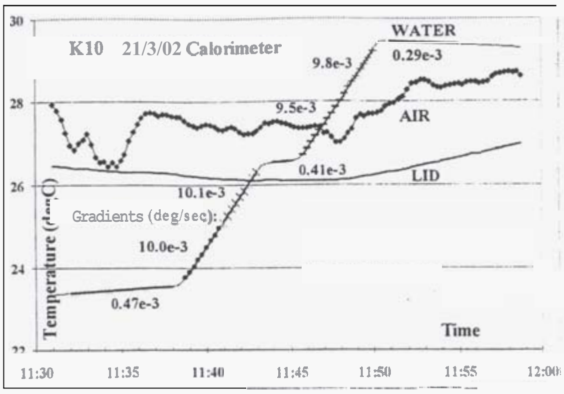

Figure 3a: Calorimeter record from site KP10 measured on 21.03.02.

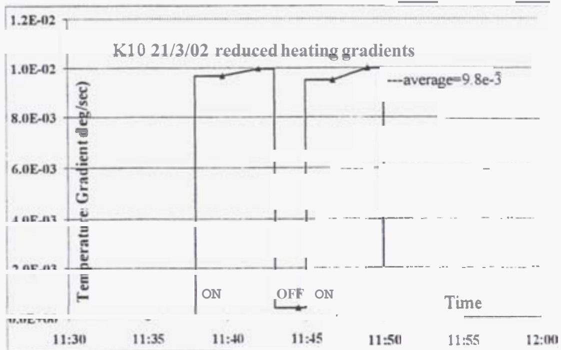

Figure3b: Sequential gradients of heating curve taken from the KPlO record (dominantly conductive heat transfer).

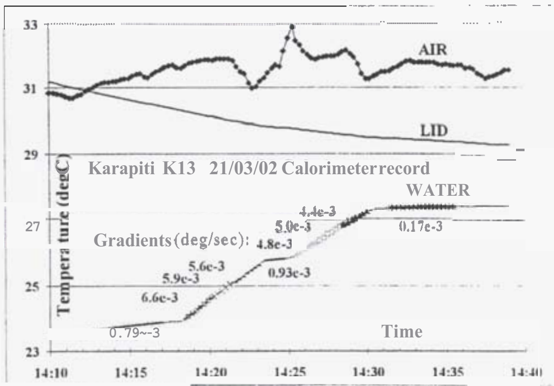

Figure 4a: Calorimeter record fkom site KP 13 measured on 21.03.02.

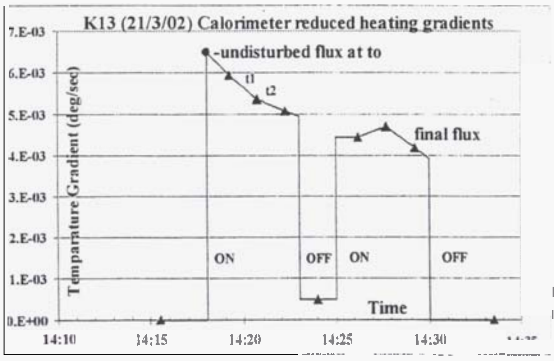

Figure 4b: Gradients of heating curve in KP13 (indicating conductive and convective transfer).

Plotting of the computed best-fit ($\Delta T/\Delta t$) values versus recording time allows a better recognition of the transfer mechanism; Fig. 3 indicates, for example, dominantly conductive transfer and Fig. 4, mixed convection/conduction.

5. REDUCING THE EFFECT OF APPARENT HEAT FLUX DECAY AND ASSESSING CONDUCTIVE FLUX

For sites exhibiting a constant gradient pattern, as shown in Fig.3b, we assumed that the average flux is the best estimate of the undisturbed Qo value and that no further reduction is necessary. However, for most other sites some reduction is required.

Temperature logging at shallow depths (– 50 mm) beneath several calorimeter sites during recording indicated small irregular changes, usually < 1 deg C, in soil temperatures over periods of c. 30 min. These do not significantly affect the conductive transfer. The overall decline of the apparent heat flux, as shown by Fig. 4b, is therefore caused by an overall decline of convective transfer. This could involve two processes: a) the vapour flux diverges as soon as the calorimeter is placed on the ground thus reducing the flux beneath it; b) the pressure directly beneath the calorimeter increases, thus causing a decrease of the shallow vertical pressure gradient and the vapour flux.

It was found that the normalized decline of the apparent flux, Qa, is proportional to the elapsed period $\Delta\tau$ between when the meter was placed on the ground and the time of the midpoint for which the drift-reduced gradient in equation (3) was computed, i.e. $(\Delta Q/Q) \sim \Delta\tau$.
This points to an exponential decay of the form:

$$\ln Q = c\Delta\tau + b, \qquad (4)$$

where ln Q is the magnitude of the convective flux at time $\Delta\tau$, and c and **b** are constants which can be obtained from observed data sets of Q and $\Delta\tau$. For $\Delta\tau = 0$, Qo is given by exp(b). The uncertainty in assessing Qo can be reduced by using a best-fit exponential function for at least two data pairs. Reduced, (Qo), apparent final heat fluxes, Qf(a), and elapsed period ($\Delta\tau$) at sites re-occupied during the field tests are listed in columns 6, 7 and 8 of Table 1.

It was found that the plots of shallow soil temperatures versus depth were non-linear at all calorimeter sites. They closely resembled a logarithmic curve when plotted, for example, as temperature difference (T_z-T_{BP}) versus depth z. The temperature Tz at depth z can be predicted by an empirical function of the type:

$$\exp[C_1(T_{BP}-T_z)]=C_2 .z + C3 \qquad (5)$$

where C_1, C_2 and C_3 are constants. For most sites C_1= 0.038, but at **KP4,** 11, and 12, C_1=0.025. The T_{BP} values were computed for each site using the local barometric pressure. The function (5) has been used to assess the best-fit near-surface temperature gradient (1-5 cm depth) and the appropriate z_{BP} boiling point depths, which are listed in Table 1.

6. SHORT- AND LONG-TERM REPRODUCIBILITY

Reproducibility of the heat flux measurements was tested by re-occupying the same site either after a few days or after several months. The results of these tests are listed in Table 1. At several sites (KP06,10,13) the first set of data ***(shown in italics)*** gave flux values that are too high. The reproducibility of the other flux values is more reasonable. The computed conductive flux values Q-cond (column ***5***) for each site vary less (usually <10%) than the corresponding total flux Q_0 values (column ***6***). Observed variations greater than 10% in Q_0 are inferred to be caused by changes in the convective component. It is likely that sites with high flux values were occupied before thermal stabilisation had been reached. In all 3 cases, site preparation involved the removal of minor plants (moss) and thin surface soil. Such sites require longer stabilisation. The good short-term reproducibility at other sites implies that the effect of different ground contacts must be small.

7. HEAT TRANSFER AND STRUCTURE OF STEAMING GROUND

The observed large changes in heat flux led us to a more detailed investigation of the soil parameters at sites KP 04B, ***06,*** 10 and 13. For this, detailed temperature profiles were measured, followed by some closely spaced (vertical) soil sampling. The dry, wet, and particle densities of each sample were determined in the laboratory yielding derived parameters, such as specific moisture content, porosity, saturation, and thermal conductivity (Bromley and Hochstein, 2001). For comparison, selected parameters were plotted versus normalized depth (z/z_{BP}).

The plots show that at sites with shallow boiling point depths (z_{BP} <0.15 m) a typical temperature and saturation (moisture) structure exists, which is shown in Fig.5 for site KP10. A similar plot was obtained for site KP **04B.** The normalised (T_z/T_{BP}) data show scatter, some decreasing with depth; this reflects the effect of daily temperature variations and near surface inhomogeneities. The Tz data can be fitted by a curve (equation 5), which indicates a quasi-linear segment close to the surface. Below boiling point depth, the temperature in the 2-phase zone is constant. Since saturation and moisture content at depths $z > z_{BP}$ is less than that at the level with maximum condensation ($z < z_{BP}$), a downward flow (counter flow) of liquid droplets can be inferred, which is required to maintain equilibrium. Thus some heat transfer at this site is associated with a natural 2-

phase flow (vapour upwards – liquid downwards). Vaporisation of the downward moving liquid results in a 'heat-pipe' effect. The temperature structure in Fig. 5 has some affinity with that found in laboratory heat pipe studies for small vertical pipes of porous material, with boiling at the bottom (Bau and Torrance, 1982).

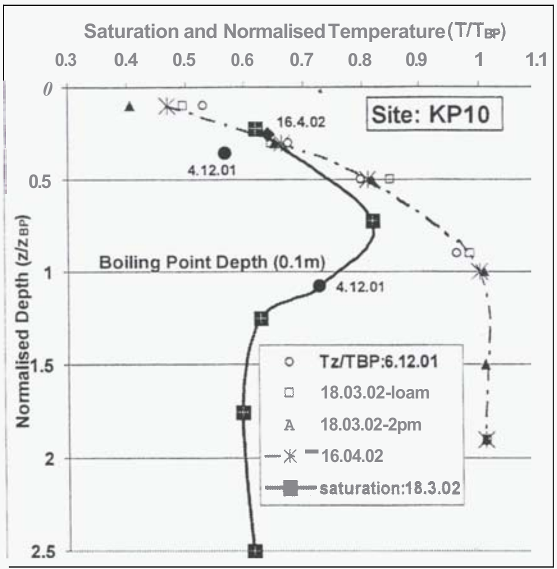

Figure 5: Normalised KP10 temperatures and moisture saturation of soil samples (typically 5 cm long), versus normalized depth

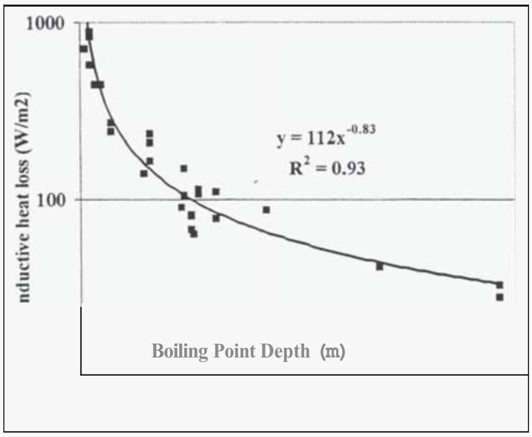

Figure 6: Conductive heat losses at all sites plotted against boiling point depth.

At other sites where z_{BP}>>0.15 m, the temperature-depth curves also show an overall exponential decline, asymptotically approaching T_{BP}. The temperature gradients, and the calculated conductive flux values, however, decrease continuously with depth below .05 m. These findings can be explained by assuming that a heat pipe mechanism also operates at steaming ground sites where z_{BP} >> 0.15 m.

Since the conductive heat transfer within the near-surface layer could be disturbed when a calorimeter is placed on site, we also monitored the apparent moisture content of the layer by using a time-domain reflectometer (TDR) with its probes inserted horizontally at depths of .05 and 0.1m beneath the calorimeter at site KP 13 and KP 11. The soil conductivity was monitored during the whole test but no significant changes in apparent conductivity and, hence, moisture content could be recognized.

A plot of the shallow conductive heat-flux (1-5cm depth) versus the boiling-point depth for all sites reveals a non-linear relationship, illustrated in Fig. 6, that is approximated by a power law equation:

$$\text{Q-cond (W/m2)} = 112. z_{BP}^{-0.83} \quad (6)$$

8. SUMMARY

The study shows that the rate of total heat discharged by steaming ground in the Karapiti area, within the greater Wairakei geothermal field, can be measured by using a (water filled) ground calorimeter. The conductive component (Q-cond) can be assessed from detailed measurements of the temperature gradient in a near-surface layer and using thermal conductivities of soil samples taken from this layer; the uncertainty of Q-cond is c. 10 %. Saturation and thermal conductivity profiles indicate that conductive transfer in the near-surface layer is maintained by condensation within and below it, pointing to a heat-pipe transfer mechanism, involving a phase change on top of a region of 2-phase flow. In addition, some free vapour can still migrate to the surface at many sites as indicated by the observed difference between Q-tot and Q-cond.

Removal of an insulating vegetation layer and levelling during site preparation can cause temporary apparent heat-flux anomalies. Longer periods of site equilibration (>1 day) are required to improve reproducibility. Placing the calorimeter on the ground can restrict the subsurface vapour flux as shown by a quasi-exponential decay of the observed total heat-flux at many sites. The effect can be reduced if data from two or more recording steps are available.

Repeat measurements showed that the conductive component (Q-cond) of the total flux (Q-tot) shows good reproducibility over periods of days and a few months. The convective component, however, shows some larger variations with time. It is not known yet whether the observed changes in convective heat-flux reflect seasonal effects.

9. ACKNOWLEDGEMENTS

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Table 1: Data of calorimeter survey of re-occupied steaming ground sites

1	2	3	4	5	6	7	8	9
Site	Date	Tgrad	k	Qcond	Q_0	Qf(a)	AT	zBP
	ddmmyy	°C/m	W/mK	kW/m^2	kW/m^2	kW/m^2	sec	m
KP03	191101	35	0.78	0.027	0.03	0.03	1140	4.3
	090402	56	0.57	0.032	0.06	0.052	480	4.3
KP04A	201101	425	1.05	0.44	0.63	0.63	420	0.22
	211101	423	1.05	0.44	0.66	0.61	420	0.22
KP04B	211101	813	(1.33)	1.08	2.35	1.5	360	0.11
	180302	804	1.33	1.07	2.1	1.33	570	0.1
KP06	***051201***	***184***	***0.89***	***0.16***	***0.83***	***0.43***	***420***	***0.72***
	160402	294	0.79	0.23	0.4	0.3	540	0.72
	190402	264	(0.79)	0.21	0.3	0.22	345	0.72
KP10	***061201***	***660***	***0.87***	0.57	***1.62***	***1.08***	***330***	***0.1***
	180302	870	0.95	0.83	0.87	0.78	600	0.1
	210302	713	1.23	0.88	0.92	0.92	540	0.1
	160402	842	0.98	0.83	0.97	0.97	480	0.1
KP11	051201	130	0.5	0.065	0.175	0.108	420	1.15
	220202	160	0.66	0.105	0.15	0.109	750	1.15
	210302	200	0.33	0.065	0.13	0.088	**555**	**1.15**
KP12	220202	146	0.77	0.113	0.33	0.29	390	1.23
	090402	154	0.7	0.107	0.19	0.15	495	1.23
KP13	***210202***	***426***	***0.56***	***0.24***	0.9	***0.39***	***1020***	***0.32***
	220202	430	(0.56)	0.24	0.48	0.35	1050	0.32
	210302	361	0.74	0.27	0.57	0.39	540	0.32
TH2	211101	166	(0.46)	0.08	0.28	0.23	480	−1.4
	250202	236	0.46	0.11	0.31	0.25	450	−1.4

Explanation of columns:

Site: KP= Karapiti, TH= Tauhara

Tgrad: near-surface gradient (°C/m) at z 1-5cm

k: thermal conductivity (W/ mK) at z: 1-5cm

Qcond: computed conductive heatflux

Q_0: reduced total flux (kW/m2)

Qf(a): apparent total heatflux at AT

AT : ground contact time in sec for Qf(a)

zBP: depth (m) of boiling point temperaure