Aspects of Natural Heat Transfer of a Geothermal System in Moderate Terrain: the Greater Waiotapu Geothermal System, New Zealand

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ABSTRACT

A numerical model of the Waiotapu, Waikite and Reporoa geothermal systems, New Zealand was previously presented by Kaya *et al.* (2014). In the present study, the same model is used to further investigate the natural state fluid and heat flow within these fields and their interconnectivity. In particular a more detailed investigation of heat flows from drainage areas is made in order to compare estimates of the heat outputs using two independent methods: direct heat loss surveys and the chloride flux method. The investigation allows evaluation of the effect of heat pipe mechanism within the great Waiotapu system. The model reproduces lateral thermal fluid flow beneath two dacite domes and the resultant demagnetization of these domes by ascending vapour produced, in turn, by shallow boiling. The cooling effect of advective, terrain-induced colder inflows on the temperature distribution in exploration wells was also studied thus developing an understanding of interaction of advective groundwater and convective thermal flows in mountainous terrain systems.
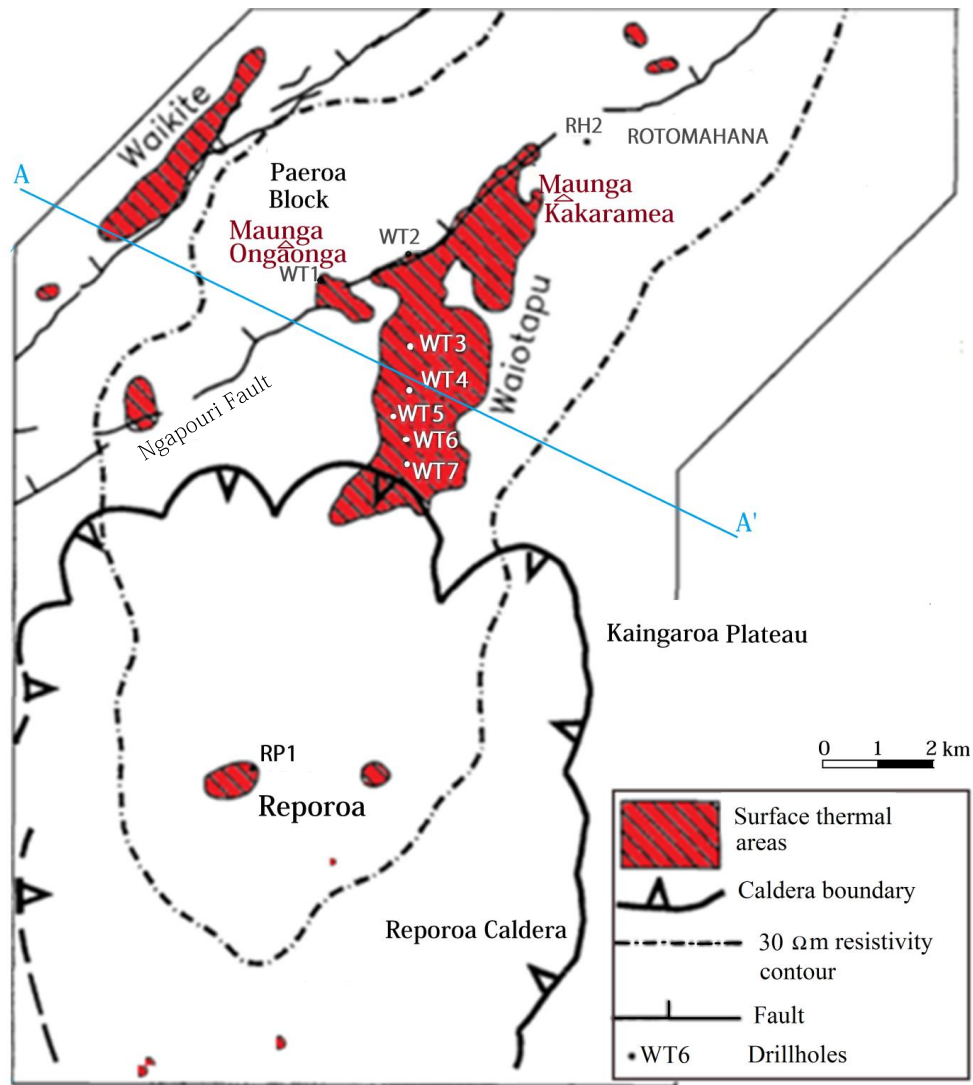
1. INTRODUCTION

The Waiotapu, Waikite and Reporoa geothermal fields lie on the eastern side of the Taupo Volcanic Zone (TVZ). Geothermal fluids from these fields reach the surface as separate watersheds. Figure 1 shows the locations of surface thermal areas of these fields. Based on published geological, geophysical, and geochemical surveys and using some recently measured field data (Kaya et al. (2014), a numerical model was set up to investigate the underground movement of hot and cold flows and to elucidate the gross permeability structures within the region. The results of the modelling study supports conceptual models which interpret the Waikite field as an outflow from the central Waiotapu field and show that the Reporoa field is also supplied by some lateral flow from the Waiotapu parent system. Therefore, these three systems are defined in terms of a single, greater Waiotapu system in this study.

The Waiotapu geothermal field, located at the northern end of the Reporoa Caldera, is the largest of the 20 major geothermal areas in the TVZ with respect to the extent of its active manifestations (17 km^2) (DSIR Bulletin 155, 1963). The Waiotapu manifestations include areas of steaming ground, thermal lakes, minor fumarolic activity associated with collapse craters, mud pools and surface alteration involving perched acid-sulphate fluids, and thermal springs.. Many of the surface manifestations are impressive and unusual and the field has been protected since 1990 as a scenic reserve by the Waikato Regional Council. Early geological, geophysical and geochemical studies were described in a comprehensive report (DSIR Bulletin 155, 1963). Subsequent geological, geophysical, and geochemical studies have been summarized in a special 1994 issue of the *Geothermics* journal.

Seven exploratory wells were drilled between 1956 and 1958, to depths of 500 m to 1100 m, across the Waiotapu field. Because of the poor discharge characteristics and scaling of the wells, Waiotapu was not considered for power production development, after 1963 when the first comprehensive geoscientific study was published (DSIR Bulletin 155, 1963).

The Reporoa geothermal field lies in the Reporoa Caldera, about 7 km to the south of the Waiotapu field. Low resistivity anomalies indicate an area of about 10 km^2 of concealed altered rocks. Two small thermal areas within the Reporoa field are characterized by thermal springs, a few hot pools, and minor thermal ground with a total surface heat loss of about 45 MW (Banwell, 1965). Well RP1 was drilled near hot springs in the center of the Reporoa caldera to a depth of about 1340 m in 1966 and revealed rocks of moderate permeability. A significant temperature inversion is a characteristic feature of the temperature log of this well (Figure 4). Low resistivity anomalies extend southward from the Reporoa field towards the Waikato River, indicating an extension of concealed thermally altered rocks. These host a minor thermal outflow marked by two low temperature springs (Golden Springs) with heat losses of about 5-10 MW (Bibby *et al*., 1994b; Lynne, 2009).

Active circulation of cool ground water in mountainous terrain can cause an advective disturbance of a thermal regime. Because of the higher piezometric levels beneath mountainous terrain in the study area (the Maungaongaonga and Maungakakaramea domes shown in Figure 1), the hydrological setting of the northern part of the Waiotapu field can induce forced convection. Many advective systems are associated with deep infiltration and deep secular flow paths transferring some heat from the thermal regime in the upper crust to small discharge centres (Hochstein *et al*., 2013). These phenomena can be seen in wells in the Waiotapu and Reporoa fields whose temperature inversions are characteristic feature of cold advective inflows and in the Reporoa well.

Figure 1. Location of the Waiotapu, Waikite and Reporoa geothermal areas in the TVZ (modified from Wood (1994)).

The Waikite field lies about 5 km to the NW of the centre of the Waiotapu field; thermal springs occur along a ~5 km long stretch of the Paeroa Fault (Figure 1). The springs discharge Cl-HCO$_3$ type waters and transfer anomalous heat at a rate of about 43 MW (Glover *et al.*, 1992). They also deposit travertine, in contrast to the Waiotapu and Reporoa springs which deposit silica sinter. Concealed low resistivity rocks at depth have been traced from Waikite to the Waiotapu field (Bibby *et al.*, 1994b).

Several conceptual models have been proposed for the three fields. An early conceptual model suggested the existence of three independent geothermal fields (Healy, 1974a, 1974b), a concept held until the late 1970s for the Waiotapu and Reporoa areas while it continued to be used until the 1990s for the Waikite area (Glover *et al.*, 1992). Later studies provided evidence that the Waikite area is an outflow structure of the Waiotapu parent system. This was confirmed by the interpretation of isotope studies (Stewart, 1994) and the finding of a deeper, coherent, low resistivity structure linking Waikite and Waiotapu (Bibby *et al.*, 1994b). Kaya *et al.* (2014) undertook a numerical reservoir simulation study in order to check which of the conceptual models best explains these three geothermal fields. For the present study the same numerical model has been used to further investigate natural state fluid and heat flows within these fields. The results from the numerical model allowed us to study in detail some anomalous heat transfer features, namely:

1. Concealed shallow outflows beneath two dacite domes.
2. Advective flow as seen in the temperature logs of Waiotapu and Reporoa wells.
3. Massive boiling at shallow depths beneath Waiotapu field supporting extensive steaming ground.
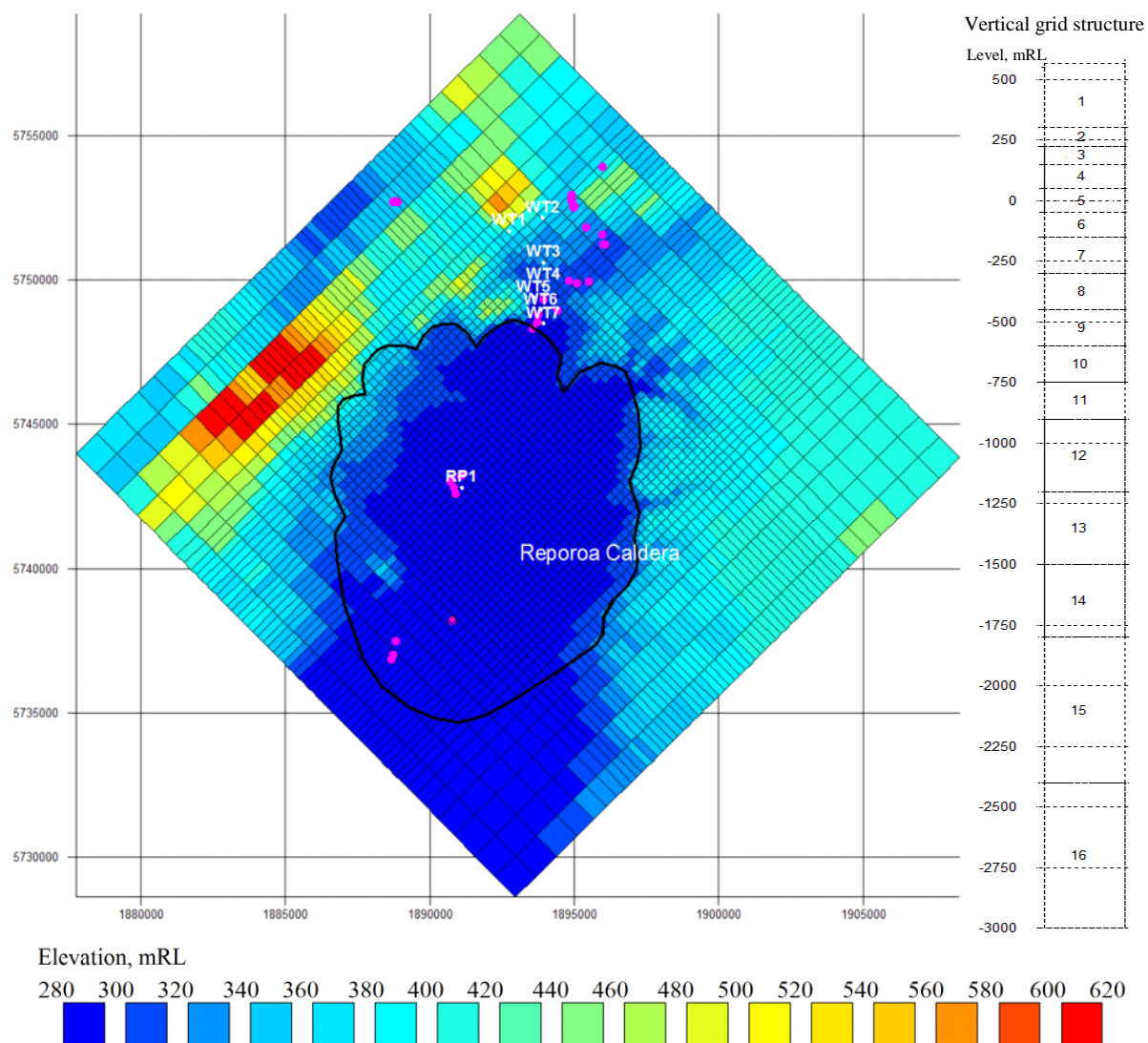4. Heat pipe mechanism indicated by some imbalance of different natural heat loss modes.

2. THE GREATER WAIOTAPU GEOTHERMAL SYSTEM

2.1 Description of the numerical model

The large scale numerical model constructed by Kaya *et al*. (2014) represents the greater Waiotapu geothermal system which includes the Waiotapu, Reporoa and the Waikite fields. This model was set up in order to test ideas put forward in various

conceptual models, to represent the natural state heat and mass transfer as indicated by the observed thermal discharges in each thermal field, and to reproduce the temperature profiles observed in the deep exploration wells.

A plan view of the model grid is shown in Figure 2. It covers an area of 450 km^2 with a regular rectangular grid. The smallest grid block size is 250 m x 250 m. This level of discretization allows a reasonable level of detail within each area, with each well in the Waiotapu located in a different model column. The locations of the exploratory holes and the thermal manifestations in Figure 1 define approximately the N-S extent of the model. The NW and SE orientation of the model aligns with the dominant SW-NE trending structural features, such as the Paeroa Fault Zone and the Ngapuri Fault (Figure 1).
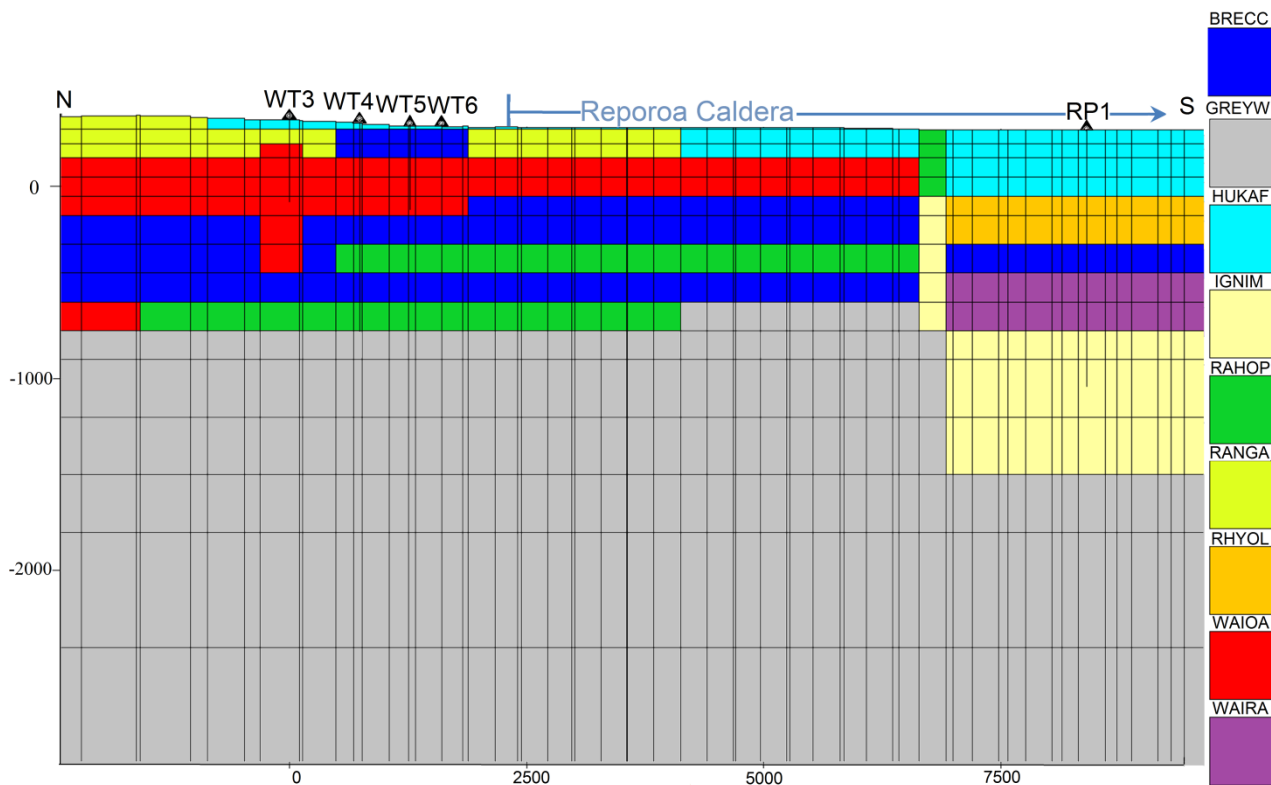

Figure 2 Surface elevations for each column, areal and vertical grid structure of the model

The spatial pattern of active surface manifestations is an important simulation constraint. The pattern of discharging thermal springs is shown in Figure 2 by pink dots. Surface manifestations data are based on the surveys done by Wildland Consultants (2001), Lynne (2009) and Newson (2010). For this modelling study, the areas of high surface activity are represented by inferred apparent "spring wells" feeding from underneath the caprock. The model was set up and calibrated with AUTOUGH2 (Yeh et al., 2011; Yeh et al., 2012). The University of Auckland version of TOUGH2 (Pruess et al., 1999) and ITOUGH2 (Finsterle, 2000). PyTough (Wellmann et al., 2012), Mulgraph (O'Sullivan and Bullivant, 1995) and Tim (Yeh and Croucher, 2013) were used for data processing and visualization.

The area which encloses the Waiotapu, Waikite, and Reporoa geothermal fields (Figure 1) lies on the East side of the Taupo Volcanic Zone (TVZ). It is covered throughout by young pyroclastics which originated as ignimbrites and pyroclastic flows from a few large eruption centres, while a few smaller eruptions produced dacite and rhyolite domes (Wood, 1994). Catastrophic ignimbrite flows erupted from the now infilled Reporoa caldera and the still active Okataina centre to the North of the Waiotapu area. Both centres occur over up to 2 km deep depressions in the underlying greywacke basement but they are still recognizable by characteristic gravity anomalies (Soengkono, 2011). The model, constrained by the blocks and layers selected, as shown in Figure

3

2, can only reflect a simplified version of the geological- tectonic setting deduced from the available litho-stratigraphic information. Figure 3 shows the rock-type distribution of the model along a section between the Waiotapu and Reporoa wells.

Figure 3. Rock-type distribution along a section between the Waiotapu and Reporoa wells

In the numerical model, the locations of deep upflows in the greywacke basement were selected by using the position of major faults as well as geophysical and geochemical information. The surface of the model was set at the water table whose level followed the surface topography (http://www.linz.govt.nz/topography/topo-maps/) and data taken from Newson (1993) and O'Sullivan and Clearwater (2011). Water table levels in the model vary from a minimum of +295mRL to a maximum of +623mRL. Surface elevations used for the model are shown in Figure 2.

The base of the model is set at -3000 mRL which is deep enough so that greywacke basement is included in the lower layers across the whole model. In vertical direction, the model was divided into 16 layers, resulting in a total of 51426 grid-blocks of the model, including an atmospheric block. For a better representation of the near surface zone, relatively thin layers (75m to 100m) were used near the top of the model (Figure 2). In particular the observed temperature and pressure logs of 8 exploratory wells with temperature inversions (see examples in Figure 4) were used for the calibration of the model.

It is known that topography induced advective cold fluid flows can modify convective flows and the temperature distribution of the brittle crust (Beck *et al*., 1989; Hochstein and Zhongke, 1992). In the Waiotapu and Reporoa fields, a characteristic feature of most wells is the occurrence of stable temperature inversions caused by cold advective in-flows. The permeability structure of shallow layers of the Waiotapu model was then varied by trial and error until good fits of observed temperature and pressure data were obtained. The temperature inversions at shallow levels could be reproduced by the model (Figure 4).

The magnitude of the observed natural heat loss at known surface discharge sites is another calibration parameter that involves matching of the concealed, regional thermal fluid flow over an area of about 150 km^2, an area which encloses all known manifestations associated with the Waiotapu-Waikite-Reporoa fields. These areas and sites are indicated in Figure 1. The location and magnitude of surface heat losses can also be reproduced by the best fit model (see computed and observed heat loss data in Table 1).

The location of concealed thermally altered rocks beneath the greater Waiotapu area was inferred from the pattern of low resistivity anomalies at intermediate depths ((Bibby *et al*., 1994b);(Risk *et al*., 1994)) and the extent of magnetic anomalies indicating extensive demagnetization of exposed volcanic domes (Hochstein and Soengkono, 1997).
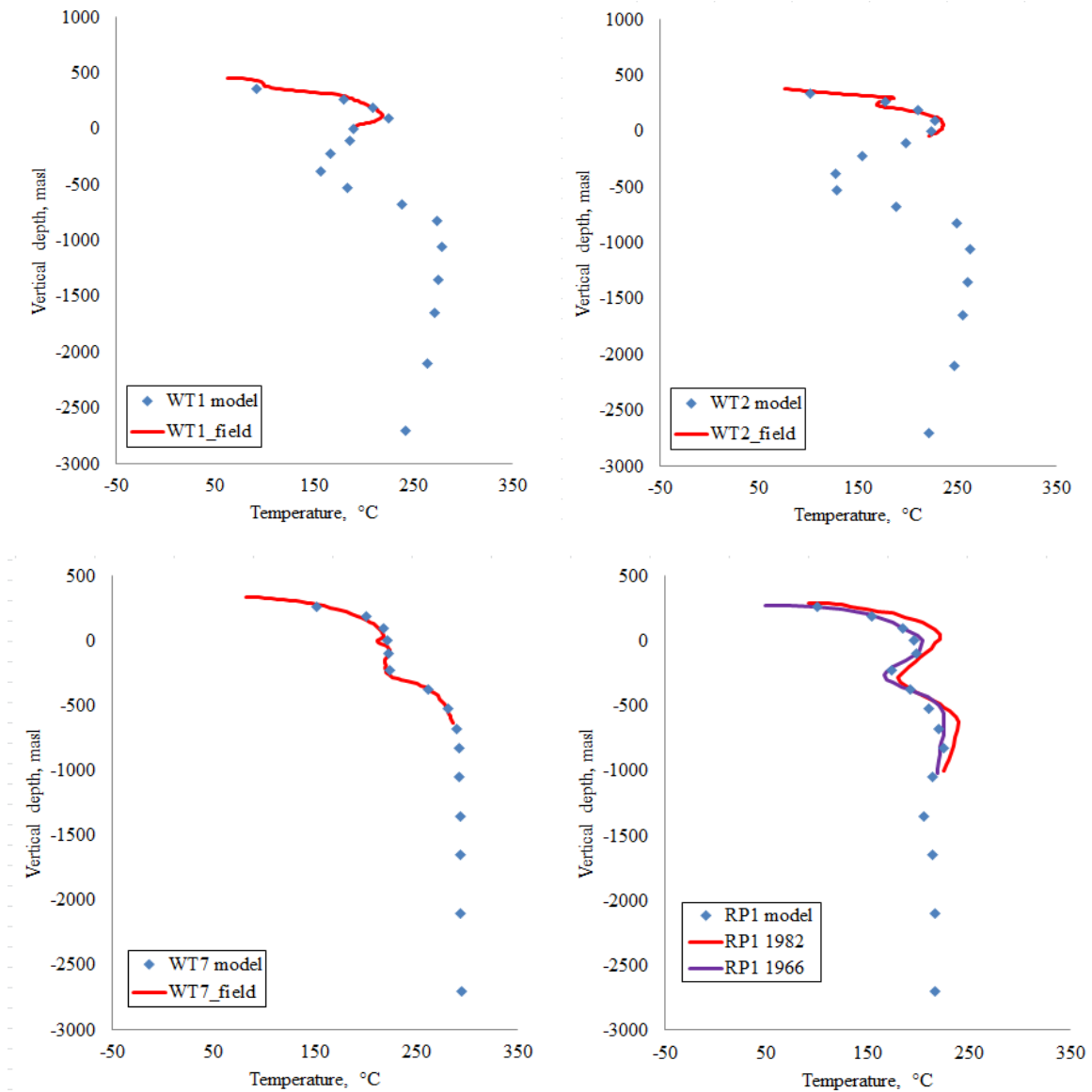
Figure 4. Temperature vs depth for wells WT1, WT2, WT7 and RP1
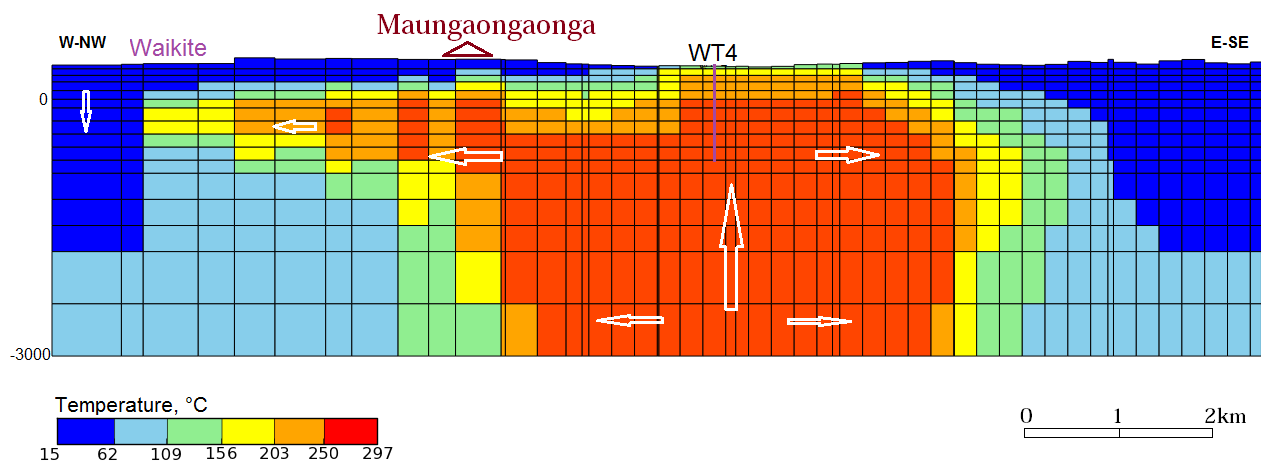
Table 1. Heat outflows to the surface.

Field	Observed heat outflow, MW	Reference	Model heat outflow, (MW)
Reporoa	45	(Banwell, 1965), (Allis, 1980)	44
	40	(Hochstein, 2007)	
	20	(Bibby et al., 1994b)	
Reporoa+ Waiotapu	540±110	(Bibby et al., 1995b)	531
	300	(Bibby et al., 1995b)	
Waiotapu	540	(Benseman et al., 1963)	487
	475±125	(Hochstein, 2007)	
Waikite	81	(Healy, 1952)	56
	70	(NZGS, 1974)	
	45	(Hochstein, 2011)	
	36	(Bibby et al., 1995b)	
Golden Springs +Butcher's pool	12	Calculated from (Lynne, 2009)	4
Golden Springs	6	Calculated from (Bibby et al., 1994b)	2.2
	2.5	Quoted in (Cody, 2007) without source	

2.2 Assessment of Fluid and Heat Flow

The numerical model of the entire Waiotapu, Waikite and Reporoa geothermal system described above is used here to investigate the underground movement of hot and cold fluid and to investigate the effect of advective flow in mountainous terrain.
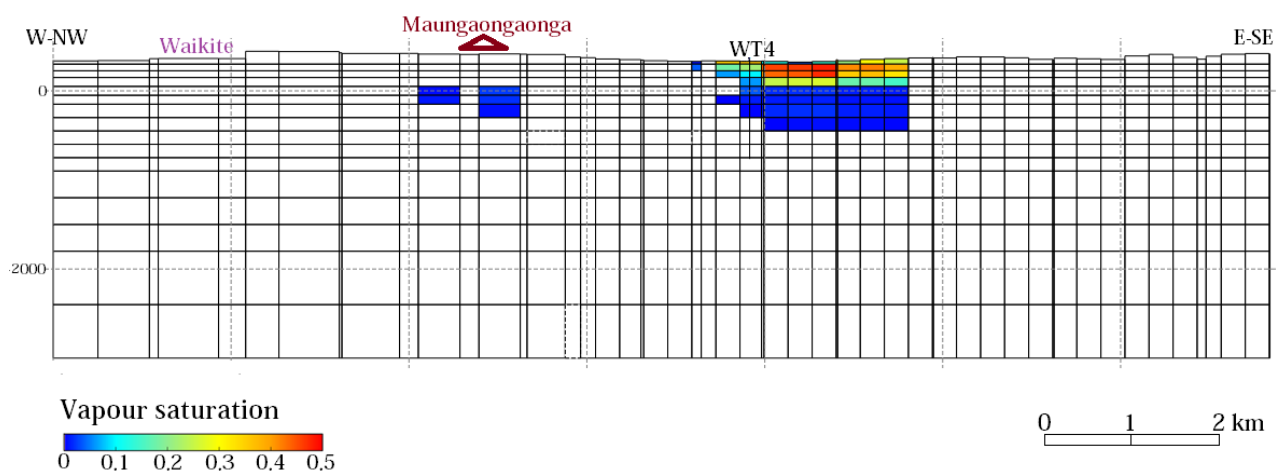
According to the model, the hot upflow mostly arises from the deep zone beneath the WT4 and WT5 wells and spreads also to the north and south of the field. There is a cold inflow in the northern part of the field from shallow depths (around 100mRL) down to around -675mRL that causes the temperature inversions in the northern Waiotapu wells (WT1 and WT2 in Figure 4).

The temperatures and mass flows within a vertical W-NW to E-SE slice through the model (A-A` line in Figure 1) are shown in Figure 5. The figure shows hot upflows occurring at the base of the model beneath well WT4 and to the east of it. Most of the shallow recharge originates in the western part of this section. The outflow to Waikite is clearly shown in this figure.

Figure 5. West-Northwest to East-Southeast vertical slice through Waiotapu showing the temperature distribution and mass flows
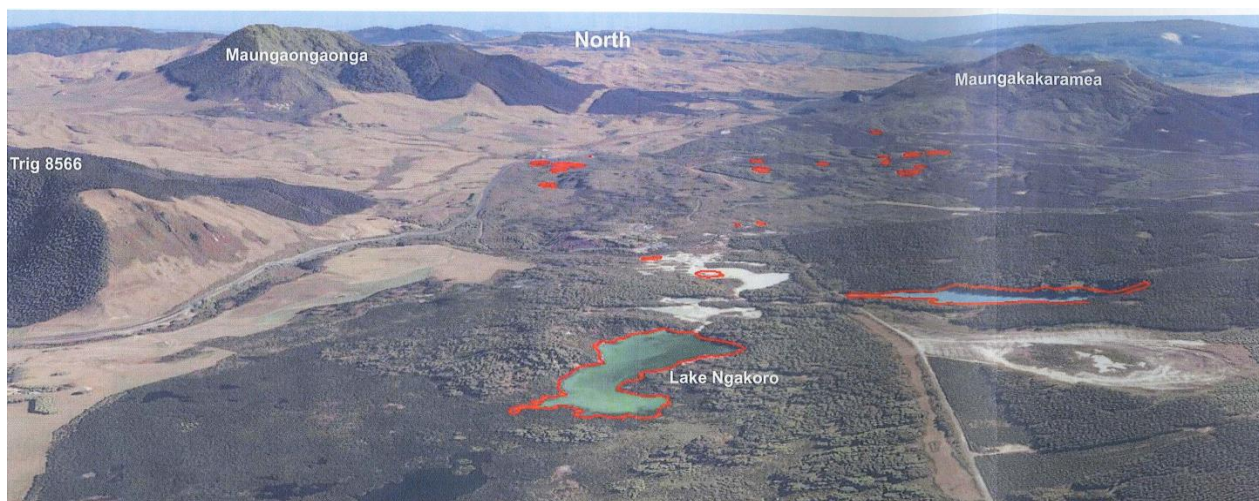
Figure 6 shows the vapour saturation distribution within the same section as that shown in Figure 5. It can be seen from Figure 6 that boiling takes place close to the 0 mRL with some vapour escaping both in the central part of the Waiotapu field and beneath the Maungaongaonga Dome.

Figure 6. West-Northwest to East-Southeast vertical slice through Waiotapu showing the vapour saturation distribution

A steam zone with a small concentration of H_2S (not included in the model) located at the top of the Waiotapu system, over time, will have condensed and would have caused alteration of magnetite to non-magnetic pyrite. This paleo flux has caused demagnetisation of the whole Maungaongaonga dome as found by interpretation of magnetic anomalies (Soengkono and Hochstein, 1996). The same phenomenon has also occurred at the Maungakaramea Dome (Figure 7). Our numerical model explains the lateral flow to Waikite and hence, the observed patchy vapour discharge through the dome.

Figure 7. The central Waiotapu geothermal field looking north (Smith, 2013). Red lined areas are associated with significant thermal heat loss.

A good match was obtained for the T profile of the RP1 well (Figure 4) involving concealed hot inflows occurring at levels of around 0 mRL and between -500 to -800 mRL with a cold inflow separating the two. Many different locations and magnitudes of deep hot upflows were tested when trying to reproduce this particular T inversion. It was not possible to obtain a good match for the RP1 well temperatures and the Reporoa surface heat output without introducing a deep hot upflow beneath the Reporoa field. In selecting the location of possible hot upflow centers beneath the Reporoa field, results of resistivity surveys (Bibby *et al*., 1994b) and the location of faults within the Reporoa caldera (Nairn *et al*., 1994) were considered.

For the RP1 well, the high temperature water in the model comes from separate hot upflows in the Reporoa caldera as well as the hot upflows beneath the Waiotapu wells WT4 and WT5. In the model, cold water flows towards RP1, between about -300 mRL and -100 mRL, from the West and South-West. This result was achieved by assigning a high horizontal permeability to the western and south-western parts of the model. It is possible to obtain adequate heat flow to the surface at Waikite without introducing any deep hot upflow beneath this area. Hence our model supports the interpretation that Waikite is indeed an outflow from the Waiotapu field.

In the model, a total mass flow rate of 486 kg/s is associated with the deep Waiotapu upflow, while there is an upflow of 105 kg/s to the North-West of the RP1 well, and an upflow of 75kg/s to the South of the RP1 well. These mass inputs vary between 2.5 and 90 kg/s for each grid block and their enthalpy varies between 1000 and 1300kJ/kg.

Advective flows:

The occurrence of advective flows in the Waiotapu area was already postulated by Newson (1993) when modelling the temperature profiles of the Waiotapu wells. Newson also inferred an associated pattern of subsurface, terrain-induced flows which are shown in a modified form in Figure 8. This figure shows infiltration, groundwater flows, high ground water discharge, geothermal discharge and the major faults (modified after Newson (1993) and DSIR Bulletin 155, (1963). A pink coloured line in this figure shows the boundaries of the model area.

Advective, terrain-induced, inflows of infiltrating surface waters mixing with upflowing thermal waters produce a cooling effect which can be seen in the temperature logs of all Waiotapu wells (Figure 4). The maximum of the temperature inversions occurs at about 400 – 500 m depth in each well in a permeable layer near the bottom of the Waiotapu Ignimbrite sheet. The inversion is most pronounced in the first two wells (WT1, WT2) located in the southern foothills of the Maungaongaonga dacite dome (summit 825 mRL). A pronounced temperature inversion is also observed in the Reporoa well (RP1) (Figure 4) with a temperature minimum occurring at about 650 m depth at the bottom of a thick rhyolite lava layer (Wood, 1994). High standing terrain of the uplifted Paeroa Block 7 km to the north-west of the well is the most likely (infiltration) source for this advective flow (Wood, 1994). Some cooler advective flow also affects the bottom section (top of the Kaingaroa Ignimbrite) of the same well.
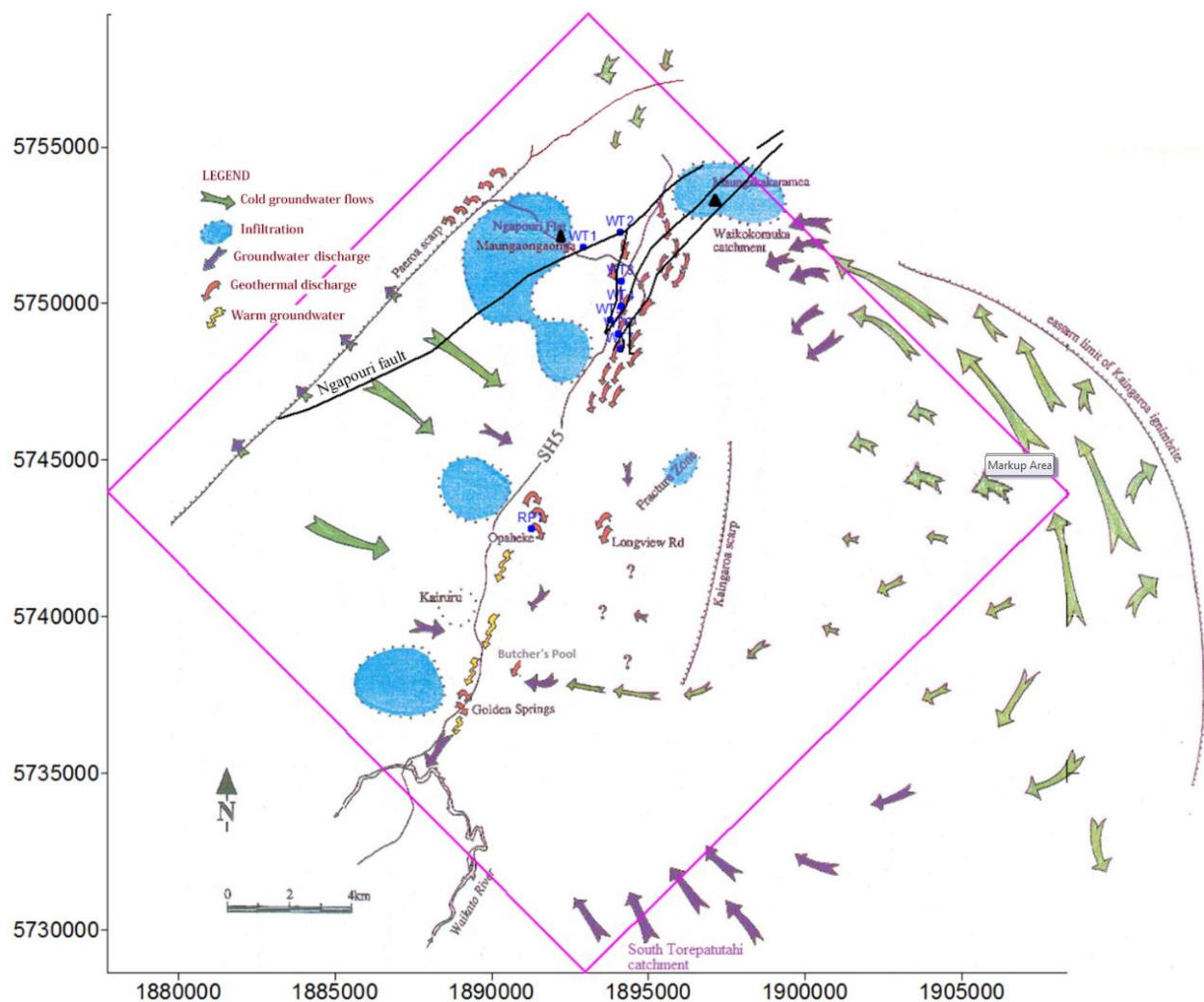
Figure 8. Conceptual model for Waiotapu, Waikite and Reporoa geothermal fields showing infiltration, groundwater flows, ground water discharge, geothermal discharge and major faults (modified after Newson (1993) and DSIR Bulletin 155, (1963)).

Boiling:

The vapour saturation at shallow, constant levels (from 400 mRL to 100 mRL) in the Waiotapu geothermal field is shown in Figure 9. According to this figure, the highest vapour saturation occurs in the eastern part of Waiotapu. This result is consistent with the observation that this area exhibits an accumulation of vapour-discharging manifestations such as hot pools, mud pools and extensive thermal ground as shown in Map 1 of the DSIR Bulletin 155, (1963).
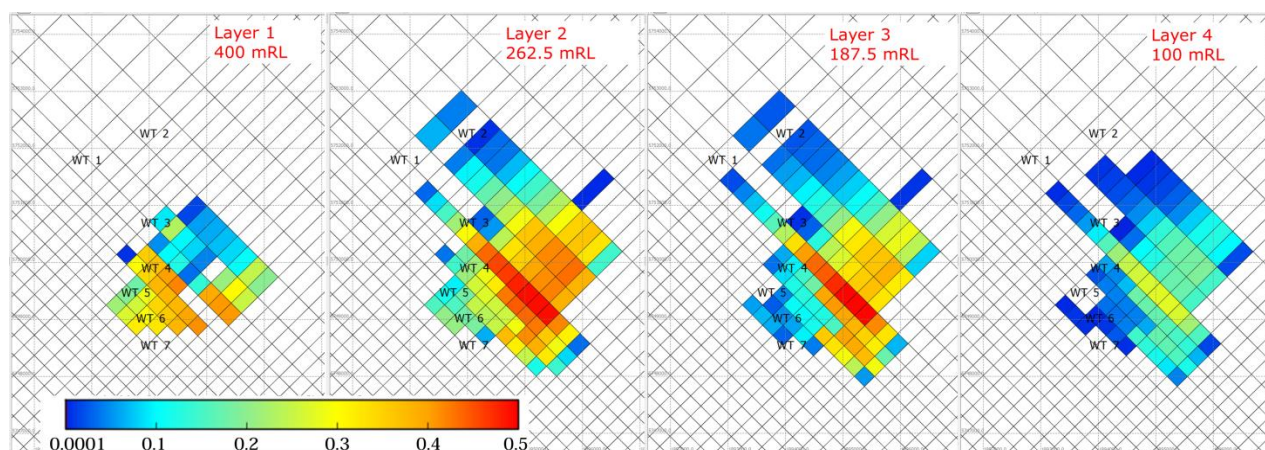

Figure 9. Vapour saturation at shallow levels at shallow levels in the Waiotapu area

Excessive and confined boiling occurs at upper levels beneath Waiotapu Field. According to the vapour saturation distribution at shallow levels (Figure 9) high vapour saturation values are observed above the upflow zones. This indicates the connection with the deep upflow centre.

Surface heat loss data and "heat-pipe" mechanism

In geothermal reservoirs, heat transfer by a heat-pipe mechanism involves some counter flow of steam and water driven by heat flux and buoyancy (Figure 10). An added heat flux results from evaporation of a deeper liquid-phase, producing an upward flow of vapour which descends after partial condensation due to buoyancy,. This counter flow of steam and water gives rise to some enhanced heat transfer. Heat pipes in horizontal systems are also possible and are driven by capillarity instead of gravity. A number of geothermal reservoirs exhibit heat-pipe action, including the Geysers, Larderello and Matsukawa fields (Amili and Yortsos, 2004).
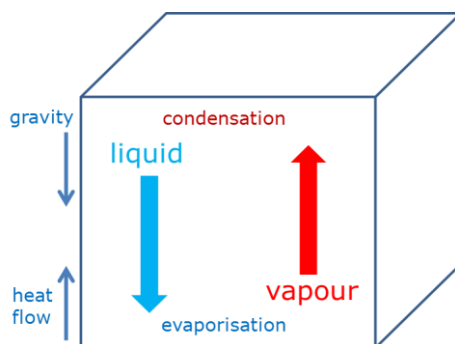

Figure 10. Simple heat pipe process

In heterogeneous systems, changes in permeability can induce saturation changes, driven by both capillary and gravity effects. Stubos *et al*. (1993), McGuinness (1993), Mcguinness et al. (1993) and Woods and Green (2000) explored in detail the factors that constrain the extent of a heat pipe.

The quality of the observed surface heat loss data over the greater Waiotapu system is variable and their uncertainty is relatively large. Table 1 shows data published in the literature for natural heat outputs to the surface of the Waiotapu, Reporoa, Waikite fields and the Golden Springs – Butcher's pool area (values shown in a bold font represent actual field measurements, those underlined green fonts represent the values calculated from Cl- flux measurements). As can be seen from this table, the measurements show a wide range.

The heat transfer at the surface of a geothermal system involves different modes of discharge whose proportional contribution to the total losses can vary from field to field. At Waiotapu, for example, about 50% of the inferred total anomalous heat discharge of about 500 MW involves evaporation losses from hot lakes and pools whereas about 26% of the total anomalous heat discharged is from steaming and hot ground, with the remainder of ~ 24 % being attributed to direct discharge of thermal water (percentages according to recent surveys by Smith (2013) and for steaming ground only cited by Benseman et al. (1963). At Reporoa ,similar proportions are indicated for these losses: namely, about 45 % for evaporation, about 40 % for steaming ground, and 15 % for direct discharge of thermal water (Hochstein, 2007). At Waikite, most of the losses are by direct discharge of thermal springs (Healy, 1952).

The dominant evaporative losses observed at Waiotapu are associated with boiling at shallow levels which has sometimes produced hydrothermal eruptions, resulting in the creation of craters now occupied by hot lakes and pools (the famous Champagne Pool, for example).The total heat discharged to the surface over this field was calculated by summation of heat loss from 'spring wells' and heat discharged from the uppermost model layer to the surface which produced a total loss of 487 MW (listed in Table 1).

Since the Cl constituent of the thermal fluids does not react with the reservoir rocks, the total Cl content discharged at the surface by creeks and ground water can be used to assess the heat losses associated with the transfer of hot chloride waters (Ellis and Wilson, 1955; Hochstein, 1988). The chloride flux method is based on the assumption that the ratio of enthalpy to chloride concentration from the deep reservoir is constant and that all the chloride in the upflowing geothermal waters is fully discharged through surface features above and outside the reservoir. Hedenquist (1991) assumed for Waiotapu a homogeneous upflow of deep thermal waters of ~300°C at >1000m depth. Newson (1993) used the same approach in her model to predict a total heat loss (Q) of about 315 MW for the Waiotapu field. Using different $\Delta Q/\Delta Cl$ values, surface losses between about 200 and 300 MW were calculated by Bibby *et al.* (1995b) for Waiotapu..

The large difference between heat losses from surface surveys (~500 MW) and the Cl method (200 to 300 MW) indicates problems with the assumptions made for one of the methods. In order to explain this anomaly it should be noted that over 130 MW heat is transferred at Waiotapu by steaming ground and fumaroles (Benseman *et al.*, 1963). Part of that heat transfer involves already some counter-flow of rising vapour and down-flowing condensate. Such a heat-pipe mechanism (counter flow of water and steam driven by gravity) allows a large transfer of heat with very little discharge of hot, chloride water. Hochstein and Bromley (2005) also proposed a heat-pipe mechanism for shallow depths in the Karapiti thermal area (Wairakei) to explain the fluid movement and phase changes in steaming ground. There may be a large heat transfer involved with the heat-pipe mechanism but only a small mass transfer. Hence, heat loss values based on Cl flux should be regarded as lower bound values. The assessment of heat loss from

steaming ground during the old (1955-58) surveys was based on visual grading of stunted vegetation and has not been checked since. According to Smith (2013), the best estimate of heat outputs of the main Waiotapu field based on Cl fluxes is between 250 and 300 MW, whereas both the recent and older surveys indicate a total loss of at least 500 MW. This discrepancy of > 40% points to the presence of a heat-pipe mechanism.
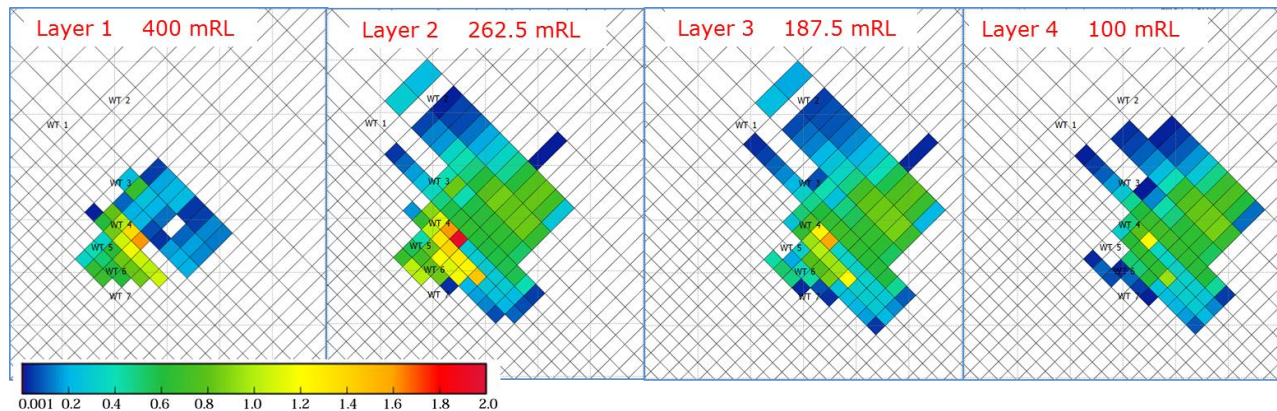

Figure 11. Vapour mass flow distribution at shallow levels

Vapour flows obtained from the numerical model are shown in Figure 11 for the same layers as those shown in Figure 9. It can be seen from Figure 11 that there is a strong upward flow of vapour at shallow levels in the central Waiotapu field. The effect of liquid counter flow is not visible in these figures. But it should be noted that most of the direct discharge represented in the model involves "spring wells" which are located at Layer 6 (-100 mRL).

3. CONCLUSIONS

In this paper, a numerical model of the greater Waiotapu geothermal system is presented which includes the Waiotapu field and the surrounding Waikite- and Reporoa fields, each with their own characteristic thermal manifestations. The model has been used to investigate subsurface movement of thermal and groundwater flows within the fields and surrounds and to model the effect of advective flows in mountainous terrain. The model was calibrated in its natural state with respect to observed and computed natural surface heat discharges for each geothermal field and its surrounds. In addition, the permeability structure at upper levels was checked by reproducing observed pressures and temperatures in eight deep exploration wells.

The model reproduces an extensive, shallow boiling zone (above 50 m RL) in the eastern part of the Waiotapu field which coincides with surface areas associated with high heat losses, mainly due to evaporation of hot lakes and steaming grounds. The computed surface discharge of the model for this central field is 487 MW, it is of the same order as that of 540 MW obtained by older surface heat loss surveys over 50 years ago. Both computed and observed losses are significantly greater than those inferred using the 'Cl- method' indicating losses between 250 MW and 300 MW. The discrepancy between observed (as well as computed) heat loss for the Waiotapu field and that given by the Cl-flux of thermal surface waters is greater than 40 %. These points to a separate vapour (up) and condensed liquid (down) transfer involving a heat pipe mechanism. This transfer has not been accurately represented in the shallow layers of the model yet.

For the Waikite field, an adequate heat discharge rate of 56 MW was obtained with the model but without introducing a separate deep upflow. The model results show that the Waikite field is supplied by ~6 km long concealed hot outflow from the Waiotapu field reservoir thus confirming a conceptual geochemical model proposed over 20 yrs ago. The model for the Waikite outflow indicates some minor boiling beneath the young Maungaongaonga dacite dome. In the past, the vapour discharge through the dome induced an alteration of (highly magnetic) magnetite to almost non-magnetic pyrite. This produced demagnetisation (paleo-alteration) of the whole dome as shown by its observed characteristic (airborne-based) magnetic anomaly.

Modelling of the thermal discharges of the Reporoa field (~44 MW) showed that both a small concealed lateral inflow from the Waiotapu field and a separate, albeit small but deep upflow from the centre of the Reporoa caldera are required to obtain satisfactory model results. Cold, concealed, ~7 km long inflows from the NW high standing terrain are required to match the significant T inversion in the Reporoa (RP-1) well. Some cooler advective flow also affects the bottom T of the well. Similar colder advective flows, albeit over shorter distances, are required to model the T inversions in the seven Waiotapu wells. Detailed modelling of thermal systems standing in moderate terrain requires therefore recognition and understanding of advective flow structures.

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