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Large-Scale Natural Convection in the Wairakei–Tauhara Geothermal Field

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Abstract

The Wairakei–Tauhara geothermal system, located within the Taupo Volcanic Zone, has been the subject of extensive geological and geophysical research, and many numerical modelling studies. In the present study the structure of large-scale convection in the Wairakei–Tauhara system is of interest. The variables investigated are the permeability structure, the topography and the heat sources. The data used for calibration are the surface mass flow and surface heat flow, based on pre-exploitation field data. A three-dimensional model was created that is larger, deeper and simpler than current Wairakei–Tauhara models. It is large enough that the Rotokawa geothermal field is also included within the model. Many different numerical simulations were carried out using TOUGH2, exploring the effects of different permeability and heat input structures. Initial models had a very simple structure and were investigated mainly to confirm the effects, already reported in literature, of different permeability structures on the number and spacing of convective plumes. As further simulations were performed it was found that the most appropriate form of the large scale permeability structure to generate the required plume spacing was non-uniform and anisotropic. Anisotropy, when combined with a cap rock layer near the surface, and a non-uniform heat flux as a bottom boundary condition, produced three plumes with surface outflows in approximately the correct locations to represent the Wairakei, Tauhara and Rotokawa fields. The mass and heat outflows for each of the fields shows a good correlation to the field data.

Introduction

The Wairakei–Tauhara geothermal system has been the subject of a succession of modelling studies at the University of Auckland since the early 1980s (see for example, [3]). When the University of Auckland model of Wairakei–Tauhara was deepened in 2006, convection cells started forming in a ring around the outside of the model. These were suppressed by the adjustment of the deep permeabilities and the modified model was again able to give a good match to the field data. However, this experience raised the issue of what the key parameters are in the Wairakei–Tauhara model that control the large-scale convection. Therefore, it was decided to use a coarser and simpler model of the Wairakei–Tauhara area to find out what controls the large scale structure of the convective system.

Thus the aims of this work are to try and find the nature of the source of the convective plumes that create the Wairakei and Tauhara fields. It is concerned with what controls the location of these fields and whether the main control on the pattern of convection is the permeability structure or the nature of the heat source or a combination of both. Thus this new model, of the entire Wairakei–Tauhara geothermal system, is used to test parameters such as the size and shape of the heat source and the permeability structure. The aim is to adjust parameters in the new model to make it match the known temperatures and flows throughout the area.

Current models of the Wairakei–Tauhara area only reach 3.5 km below the surface, and as a result they do not encompass the whole convective system. This means the location and magnitude of the deep inflows are approximated in the model by mass injection over the bottom surface. Increasing the depth of the model will mean that these artificial deep recharge boundary conditions are no longer necessary, and will allow a new understanding of the deep structure of the Wairakei–Tauhara Field.

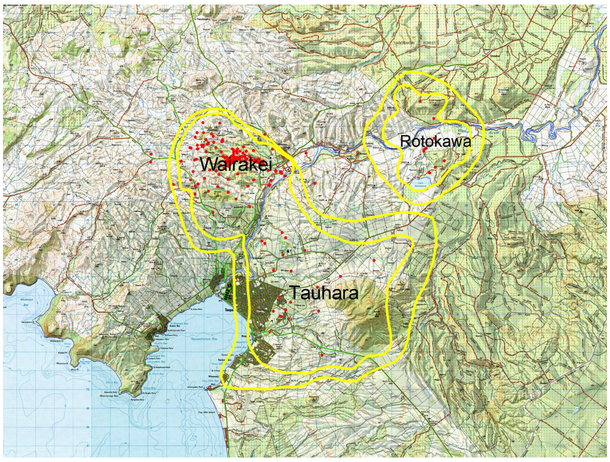


Figure 1: Wairakei, Tauhara and Rotokawa geothermal field locations. The lake at the left is Lake Taupo, and the Waikato River runs up to the north-east. The yellow band shows the resistivity boundaries

The Field

The Wairakei field is located 8 km north of Lake Taupo and sits on the north-west bank of the Waikato River. The Tauhara Field is on the south-east side of the river about 10 km south-east of Wairakei. These fields are hydrologically linked, and so, to more accurately represent the system, the two fields must be included in the model. Resistivity measurements give an outline of the boundary of the hot reservoir, as shown in Figure 1. The system area covers about 25 km^2 with a narrowing between the two main regions. About 8 km to the east of Wairakei, near the eastern edge of the Taupo Volcanic Zone, lies another geothermal system called Rotokawa. The Waikato River runs through this system, and the resistivity boundary covers about 15 km^2. The Rotokawa system seems to be somewhat separate from the Wairakei–Tauhara system even though they are close. For example, in contrast to the experience at Tauhara, there have been no significant effects at Rotokawa as a result of production at Wairakei. Both systems lie within the model that is used for this study and therefore data from Rotokawa as well as from Wairakei–Tauhara must be considered.

For the Wairakei field in the pre-production state, there were numerous active geysers, hot springs and fumeroles. These were concentrated in two main areas: Geyser Valley and Waiora Valley. In the southern part of the field a large area of steam discharge was present at the Karapiti thermal area. The natural heat flow over these thermal areas has been measured at different times and by various methods, see for example [2]. Outputs measured include heat flow from geysers, springs and mudpools as steam or water, conductive heat flow through the soil, convective heat flow through soil and steam vents, and seepage into rivers. The Tauhara field also had geysers, hotsprings and areas of steaming ground around the base of Mount Tauhara, and Rotokawa had steaming ground with a few springs into the Waikato River. The surface heat and mass outputs along with deep temperatures that will be used to match with the models created in this work are shown alongside the model results in Table 2.

Model Description

TOUGH2 (Transport of Unsaturated Groundwater and Heat [4]) is the numerical simulator used for the models in this work. The model has a regular grid consisting of 2300 columns divided into 12 layers giving a total of 27 600 blocks. In designing the grid, several criteria were specified, namely:

1. A large horizontal area was needed in order to account for the cold recharge from outside the resistivity boundary into the reservoir.
2. As well as trying to obtain plumes in the right areas, the surface mass and heat flows were also required to be matched. Therefore it was desirable to have areas where there are known surface mass flows or heat outputs fit into one block. This meant that the grid had to be rotated to fit them, and that the horizontal block size needed to be made sufficiently small.
3. The convective circulation depth is thought to be approximately 6 km, and so the depth of the model was required to match this.
4. The grid needed to fit the Eastern and Western Borefields at Wairakei into a block each. The grid was adjusted to get the Wairakei–Tauhara and Rotokawa fields roughly in the centre of the model.
5. To make computation as simple as possible, a fully saturated model was used, and so the top surface of the model was set at the groundwater level.
6. The dominant faulting direction is NE to SW. To allow for the possible inclusion of these structures in the model, it was rotated to align in this direction.

The model blocks are each 500 m deep which gives a total depth of about 6 km. This varies depending on the water table depth. Horizontally, each block is 1 km by 1 km, with 42 in the NE direction and 50 in the NW direction. The vertical sides of the model are closed boundaries, impermeable and non-conducting. This means that all velocities normal to these boundaries must be zero, and so no fluid or heat flows in or out. This is based on the assumption that the whole large-scale convective system of Wairakei, Tauhara and Rotokawa has been captured within the boundaries of the model. The top surface of the model allows recharge: i.e. fluid may leave or enter, and so the natural process of recharge of water from the surface is simulated. This is incorporated by specifying a uniform pressure at the surface. For the bottom boundary of the model heat fluxes were applied which represent the general background heat flux as well as the greater heat flow anomalies responsible for generating the geothermal fields.

A number of models were explored to try gain a better understanding of the various features of the large scale hydrology of the Wairakei–Tauhara geothermal field. These have been listed in Table 1.

For each model a natural state simulation was carried out, representing the development of the geothermal system over geological time. The parameters adjusted were the permeabilities and heat flux. The calibration variables are the temperatures, surface heat flows and surface mass flows in specific areas where

Model	**Description**	**Options**
Model 1	Flat top, variations in permeability	Permeabilities of K = 0.5, 1, 2, 5, etc. mD for heat flows of 80, 120, 160, etc. mW/m^2
Model 2	Flat top, variations in permeability	a) Uniform, anisotropic b) Non-uniform, isotropic, let K vary with depth exponentially c) A combination of a) and b) d) Inclusion of a low permeability Huka Falls layer (cap rock)
Model 3	Topography	Inclusion of varying heights of topography
Model 4	Heat input	Gaussian functions applied for each of the 3 point sources. Location, size and intensity altered

Table 1: Model Scenarios

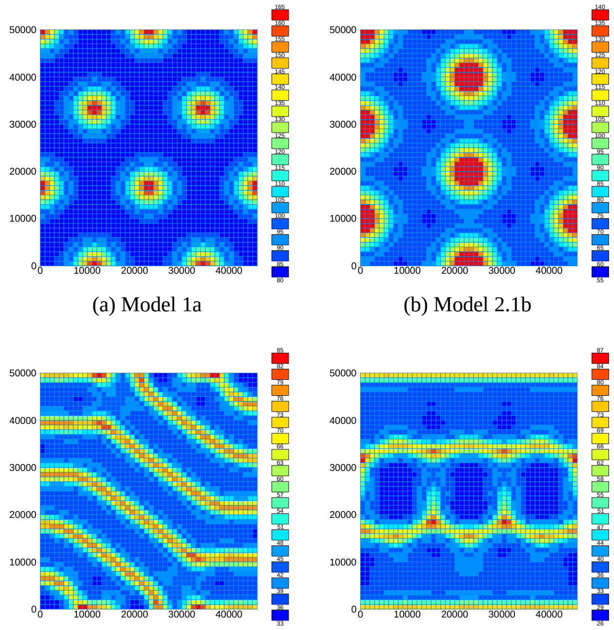
the model is required to match the known field data. Models 1 to 3 are mainly experimental, looking at what changes occur for the Wairakei–Tauhara area, and so the calibration variables were not always matched. More of interest was where the surface outflows occurred and how their values changed. For Model 4 it was hoped that the knowledge from the previous models would enable more realistic temperatures, surface heat and mass flows to be modelled.

The heat sources used for Model 4 are based on the idea that the actual heat source is probably below the surface expression of the hot plumes. For this reason a detailed representation of the actual heat source is unnecessary and has been replaced by an effective heat source. Any magmatic intrusions, magmatic fluid, etc. have been lumped together into steady effective heat sources spread over a few blocks at the base of the model.

Model Results and Discussion

This section briefly describes some of the main findings from this work, a full description of all results for different Models and permeability combinations can be found in [1]. Figure 2 shows a selection of Model 1 and 2 results. The plots show the temperatures in a horizontal layer in the centre of the model, which corresponds to a depth of about 3 km below the surface. Model 1a (shown in Figure 2a) shows the plumes resulting from an 80 mW/m^2 heat flux base input and a uniform permeability of 0.5 mD (0.5×10^{-15} m^2). These plumes are very regularly spaced over the grid, with hot upflow in the centre and cold down flow around the sides of each cell. A hexagonal cell convection regime has been reached. The distance between plumes in the x-direction is 22 km, and 15 km in the y-direction. This gives a diagonal distance of 27 km which is larger than the spacing of the fields of interest. An increase of permeability gave a decrease in the horizontal spacing of the plumes, and an increase of heat flux increased the number of plumes. From this model it was realised that convection begins at very low permeabilities.

Model 2.1 included anisotropy to allow for the analysis of the effects of fractured rock formations on hydrothermal circulation. Many of the formations in the Wairakei area have high permeability and often high horizontal permeability compared to the vertical permeability. As the ratio of horizontal to vertical permeability is increased, the spacing and number of plumes reduces. Model 2.1b (shown in Figure 2b) shows the plumes resulting from an 80 mW/m^2 heat flux base input and a horizontal permeability of 0.5 mD (comparable to Model 1a) but



(a) Model 1a (b) Model 2.1b

(c) Model 2.2b (d) Model 2.3b

Figure 2: Temperatures (°C) on a horizontal layer at the centre of Model

with a horizontal:vertical ratio of 5 : 1. Here the plume alignment shows preference for the y-direction, and the upflow area is wider and the centre of the plumes hotter than for Model 1a. Increasing the horizontal permeability changes the resulting convective regime. For these models the cell width is increased and hence the number of plumes present in the grid is reduced. It was observed that the spacing of plumes resulting from a horizontal to vertical ratio of permeability of 5 : 1 was the best for matching the distances between Tauhara, Wairakei and Rotokawa.

For Model 2.2 the inclusion of non-uniform permeability was considered. The layers which make up the Wairakei stratigraphy are very varied, but a general trend is seen of decreasing permeability with depth. This was implemented by using an exponential decrease of permeability with depth. Model 2.2b (shown in Figure 2c) shows the plumes resulting from an 80 $\mathrm{mW/m^2}$ heat flux base input and a horizontal permeability of 0.5 mD (comparable to Model 1a) but with a vertical non-uniformity factor of 100 (the permeability at the top layer of the model is 100 times larger than the bottom layer, according to an exponential decrease). There is some appearance of a steady state flow regime in terms of the regularly spaced two-dimensional rolls on the left and right edges, but at the centre of the model the middle part of the plume oscillates back and forth between two plumes. The temperature–time history of a central block shows rapid oscillations occurring, so the non-uniform isotropic models for this grid were generally transient. An increase of background heat flux shortened the length of the oscillatory plumes, and in some cases switched to the three-dimensional regime, or rolls in the y-direction rather than the x-direction.

Model 2.3 combined the previous cases of non-uniformity and anisotropic permeability. Model 2.3b (shown in Figure 2d) has an 80 $\mathrm{mW/m^2}$ heat flux base input (as with all the moedls shown), a non-uniformity factor of 100 (comparable to Model 2.2b) and an anisotropy ratio of 5 : 1 (as with Model 2.1b). The steady state convection pattern for this model is two-dimensional rolls. Model 2.3 results showed that non-uniformity of factors 10 and 100 were both viable options for models, although the factor of 100 gave results that tended towards oscillatory solutions. Overall, the combination of non-uniformity and anisotropy led to results similar to that of the non-uniform permeability model. Thus, non-uniformity has a larger effect than anisotropy on the heat and mass flows.

Model 2.4 proved that the inclusion of a cap rock could settle an oscillatory model into a steady state, and would increase the cell width / plume spacing. The topography models showed the extremely large effect even minor topography changes had on the plume formation, completely shifting the up and downflow regions.

For Model 4, instead of a uniform heat flux being applied as a boundary condition to the bottom layer of the model, a two-dimensional elliptical Gaussian function was used to represent the deep heat flux for each of the three fields. This gave control over the placement, shape and intensity of each source, as it had been found from earlier models that a uniform heat source produced too many plumes over the model area. The centre of each of the three main surface outflow areas became the coordinates for the location of the peak and centre of three Gaussian heat sources. These three heat sources were then overlapped and an overall input of 80 mW was added, to account for the background heat flux.

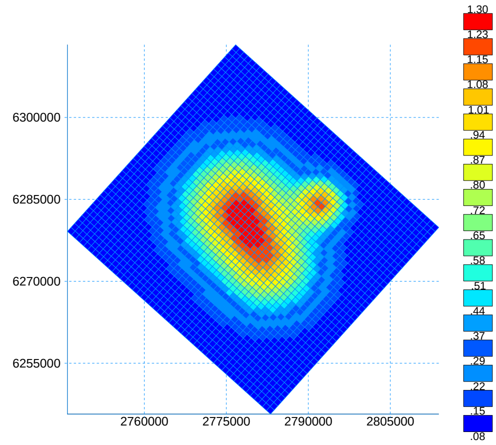


Figure 3: Non-uniform heat input for Model 4.6. The scale bar units are $\mathrm{W/m^2}$.

Various radii, locations and peak heats were experimented with in order to get the gaussian heat sources representing each field to be the best match to the surface flow data. Repressing the plumes around the edges of the model, and ensuring there was no link between the Rotokawa field and Wairakei-Tauhara proved difficult to achieve. The model shown in Figure 5 provided the best fit. All sources were circular, with the new heat inputs in the ratio 11 : 8 : 9 for Wairakei, Tauhara and Rotokawa respectively. The radius of each source was 8 km, 6 km and 3 km, and the positions of these did not lie directly beneath the surface outflows. This source distribution can be seen in Figure 3.

The total heat input and hence surface output for this model is 780 MW. This is divided into 440 MW at Wairakei (140 MW of which is actually situated between Wairakei and Tauhara), 180 MW at Tauhara and 100 MW at Rotokawa. The total mass output is 807 kg/s of which 423 kg/s is at Wairakei (141 kg/s of which is again located between Wairakei and Tauhara), 186 kg/s is at Tauhara and 120 kg/s is at Rotokawa. These values are comparable to the field data, but the Rotokawa heat output is a little low and the Tauhara heat output a little higher than re-

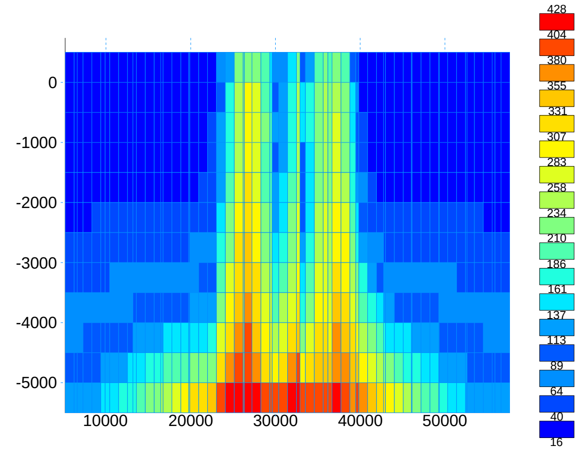


Figure 4: A NW–SE vertical temperature section, bearing 150° north, showing the Wairakei (left) and Tauhara (right) plumes from Model 4.6c. The scale bar units are in °C.

quired. A vertical slice through the model is shown in Figure 4 where the connection between Wairakei-Tauhara is visible. The temperatures at Rotokawa are lower than the field data, and the Wairakei temperatures are higher than required.

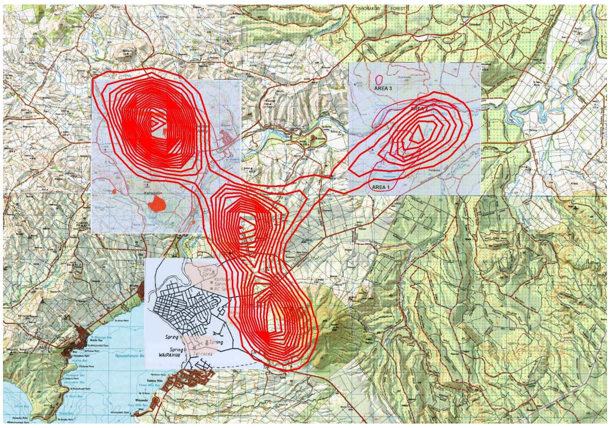


Figure 5: Surface heat flow contours from Model 4.6c including cap rock

The surface heat flows can be seen in Figure 5 which shows that the Rotokawa plume is in the correct position, south of the Waikato River, but also the upflow between Wairakei and Tauhara is not located above the river where the actual flows occur, instead it is located further south.

Conclusions

The aim of this study was to create a model that is wider and deeper than current Wairakei–Tauhara models, to avoid artificial recharge boundary conditions and to investigate what controls the large-scale convective structure. This work looked mainly at what controls the location of the fields, either permeability or heat input or a mixture of both.

Wairakei and Tauhara are hydrologically linked, and hence the model encompasses both of these fields. The large spatial area of the model means that Rotokawa geothermal field was also included, as it is located about 10 km east of Wairakei.

First a flat top steady state model was investigated with a uniform heat input and variations in permeability in terms of anisotropy and non-uniformity. The different combinations modelled enabled an understanding of what controls the spacing of plumes. The most successful models had anisotropic and non-uniform permeability, with a cap rock and with a non-uniform heat input. The non-uniform permeability was applied as exponentially decreasing with the surface value ten times that of the lower layers. The anisotropy was applied such that the x,y-directions had a permeability value five times higher than the z-direction. The cap rock was applied at a layer corresponding to where the Huka Falls formation exists. The non-uniform heat input was applied as three separate sources with a peak heat ratio of $\frac{11}{10} : \frac{4}{5} : \frac{9}{10}$ representing the Wairakei, Tauhara and Rotokawa fields respectively.

The total surface heat flow output was 780 MW, divided into 440 MW at Wairakei, 180 MW at Tauhara and 100 MW at Rotokawa. These values and their locations correspond well to the field data, although some of the Wairakei heat flow locations are a little too far south and the Rotokawa heat is a little too low. Deep temperatures within the model show 300 °C for Wairakei, 320 °C for Tauhara and 310 °C for Rotokawa, which is a little low for Rotokawa and a little high for Wairakei compared to the field data. The total surface mass flow was 807 kg/s corresponding to 423 kg/s at Wairakei, 186 kg/s at Tauhara and 120 kg/s at Rotokawa. This is summarised in Table 2.

Thermal Area	Deep Temperature (°C)		Heat Flow (MW)		Mass Flow (kg/s)	
	Field	Model	Field	Model	Field	Model
Wairakei	260	300	430	440	450	423
Tauhara	300	320	110	180	180	186
Rotokawa	330	310	210	100	191	120
Total			750	780	921	807

Table 2: Field data estimates compared to final model results

The model could be improved by the inclusion of faults. In the Wairakei–Tauhara Fields the major deep NE trending faults Kaiapo, Wairakei and Waiora act as conduits for a lot of deep hot fluid. The effect of these faults could be looked at in the numerical model by including a vertical set of blocks as a high permeability zone. They would be allocated a very high permeability value. This would also provide more clues about whether the heat is being partly drawn from Tauhara, rather than Wairakei being the main source. Also, all models explored for this work assumed permeability to be horizontally uniform. This is not true in the real system or in the current University of Auckland 9011 model. It may be necessary to introduce lateral variation in permeability along with the real topography in order to obtain a better model.

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