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# Using Reservoir Models for Monitoring Geothermal Surface Features

John P. O'Sullivan, Thomas M. P. Ratouis, Michael J. O'Sullivan

***Abstract*—**As the use of geothermal energy grows internationally more effort is required to monitor and protect areas with rare and important geothermal surface features. A number of approaches are presented for developing and calibrating numerical geothermal reservoir models that are capable of accurately representing geothermal surface features. The approaches are discussed in the context of cases studies of the Rotorua geothermal system and the Orakei-korako geothermal system, both of which contain important surface features. The results show that models are able to match the available field data accurately and hence can be used as valuable tools for predicting the future response of the systems to changes in use.

***Keywords*—**Geothermal reservoir models, surface features, monitoring, TOUGH2.

## I. INTRODUCTION

GEOTHERMAL energy is becoming an increasingly attractive option in many countries. The international geothermal power market has been growing at a sustained rate of 4% to 5% annually and almost 700 geothermal projects are under development in 76 countries [1]. This is because energy produced from geothermal resources is secure, reliable and produces almost no greenhouse gases. Also, when compared with other methods for generating electricity geothermal power plants have one of the highest capacity factors and the lowest levelized costs of electricity [2].

As [3] discusses, there has always been a conflict between the utilization of geothermal resources and the protection of geothermal surface features for cultural and tourism reasons. The increase in geothermal development has heightened this conflict with more areas being proposed for utilization closer to those that are protected.

This is particularly evident in New Zealand where in spite of its long in history in geothermal energy production, one of the most rapid increases in installed geothermal capacity has occurred in recent years. Current installed capacity has risen to over 1000 MW from 762 MW in 2010 and at times in 2014 accounted for 17% of the country's electricity mix [4]. Most of the new capacity has been developed in the Taupo Volcanic Zone (TVZ) which also hosts many of New Zealand's most important geothermal surface features (Fig. 1). The government agencies responsible for protecting the surface features have implemented a number of monitoring programs for different geothermal systems so that they are able to assess any potential impact of the increased geothermal energy production ([6], [7] and references therein).

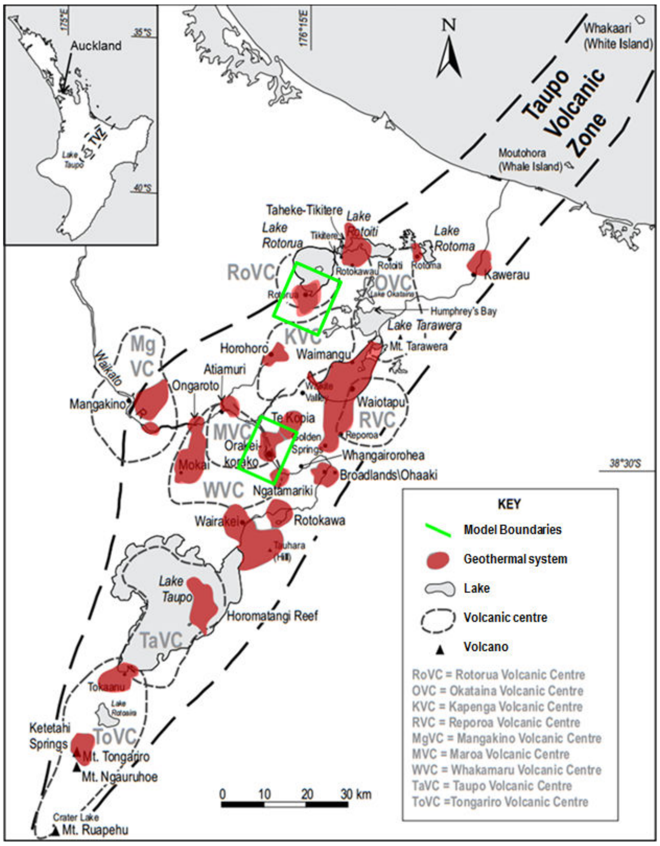

Fig. 1 Map of the Taupo Volcanic Zone showing the geothermal systems and the locations of the models discussed (adapted from [5])

The objective of this work is to demonstrate how numerical geothermal reservoir models can be used along with the monitoring programs to predict the impact of future increases in utilization on protected systems. These models will enable many different future scenarios to be investigated and help to define policies around the expansion of geothermal resource utilization. The same approach could be applied in other countries that are increasing geothermal energy production rapidly such as Turkey, Indonesia, Kenya and the Philippines.

Geothermal reservoir models are already used extensively to support geothermal energy production [8] and the technology is well established. However, these reservoir models focus on the deep geothermal resource and do not usually resolve the system accurately close to the surface. In order to accurately model the shallow zone and surface

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expressions of a geothermal system, different approaches must be used.

In the following sections two case studies are presented of geothermal reservoir models that have been developed using AUTOUGH2 [9] to accurately represent the interaction of the systems and their surface features. The first is a model of the Rotorua geothermal system (RGS) and the second is a model of the Orakei-korako geothermal system (OGS). Their locations are indicated in Fig. 1. While both systems have common features and both contain world famous geothermal surface features, the RGS has been utilized extensively for direct heat use whereas the OGS has been completely protected. In the beginning of each section the geothermal systems are described in more detail, then the models are presented and comparisons with field data discussed.

The results show that both models represent the geothermal systems and their surface features accurately and can be used as tools to assist with planning the monitoring, protection and management of the resources.

## II. CASE STUDY ONE - ROTORUA

### *A. Description of the system*

The RGS is unique in that it lies directly beneath a city and contains one of New Zealand's last remaining areas of major geyser activity at Whakarewarewa (Fig. 2). The geothermal resource and features have a strong cultural significance in terms of Māori beliefs and customs [10], high economic value as tourist attractions and energy sources, and hold remarkable biodiversity [11]. It is located within the Rotorua rhyolitic Volcanic Centre at the southern margin of Lake Rotorua (Fig. 1) and covers an area of approximately 18-28 km2 as defined by electrical resistivity surveys [12]. Reference [13] described the geology of the RGS as comprising of syn-caldera pyroclastic materials (Mamaku Ignimbrite), lava flows and domes (Rotorua Rhyolite), and lacustrine sediments.

Temperatures of over 200°C are encountered in the reservoir at depths of less than 200m and the natural surface heat flow of the RGF is one of the largest of all the geothermal systems within the TVZ. Reference [14] estimated the heat flow for the RGS to be 430MW while [15] inferred a natural state heat flow at Whakarewarewa of 300MW. High $CO_2$ fluxes are also present in the RGS with [16] recording measurements of up to 11535 d/day-m$^2$ in the Ngapuna area (Fig. 2).

The RGS has been utilized since the 1800s but intensive drilling and fluid extraction began in the 1950s. By 1985 over 900 shallow wells had been drilled and a significant decline in field pressures and surface activity had already been observed [17]. In 1982 concern about the effects of the utilization on the springs and geysers led to the creation of the Rotorua Geothermal Monitoring Programme (RGMP) and ultimately the Bore Closure Programme in 1986 [7]. This programme enforced the closure of all boreholes within a 1.5 km radius of the Pohutu Geyser (Whakarewarewa), the closure of all government-owned wells in Rotorua township, the implementation of a charging regime for extracting geothermal fluid and the introduction of a royalty scheme to promote fluid reinjection [17]. In the years that followed, the pressure in the system recovered by approximately 0.1-0.2 bar and many of the surface features also began to recover.

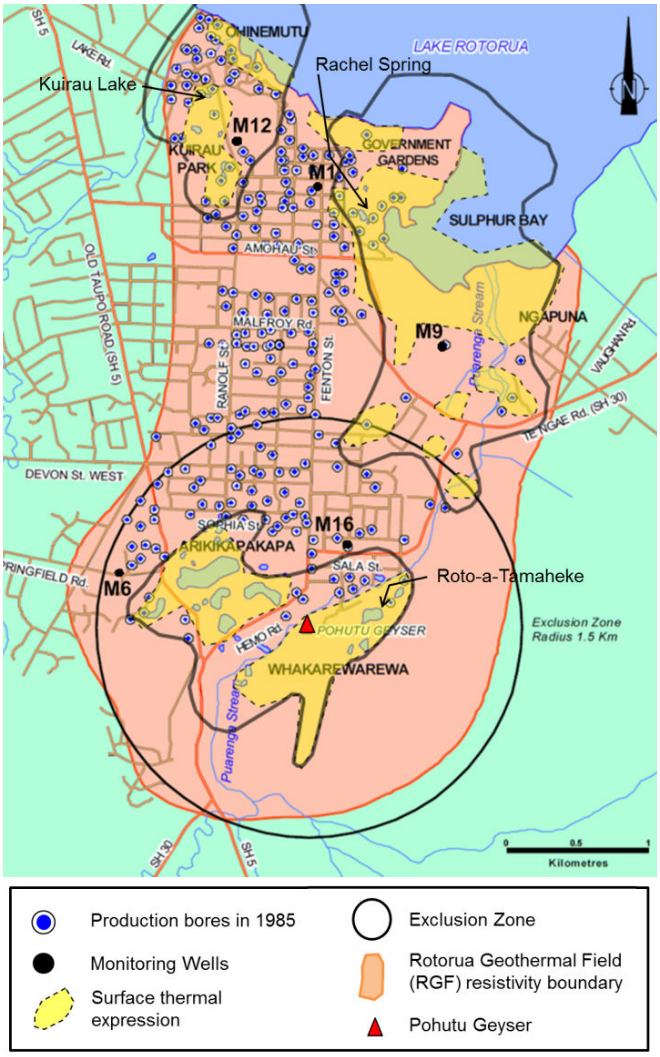

Fig. 2 Map of Rotorua showing the surface features, geothermal and monitoring wells and the resistivity boundary

In 1991 the Resource Management Act made Environment Bay of Plenty (EBOP) responsible for the management of the system and the Rotorua Geothermal Regional Plan was developed and came into effect in 1999 [18]. The plan requires that ongoing monitoring and research of the system are carried out. The reservoir model described in this section has been developed in conjunction with EBOP as part of that effort. For a more detailed description of the RGS please see [19] and the references therein.

### *B. Model Setup*

Numerical reservoir models require different characteristics in order to accurately represent the surface features of a geothermal system and their interaction with the rest of the system. They must include the shallow, unsaturated zone in the model domain and have a high vertical resolution in this area to capture the high temperature gradients. Including the shallow, unsaturated zones has two important implications. First, the model domain extends to the earth's surface and must follow the topography above the geothermal system. Second, equations of state that allow for the unsaturated zone must be used.

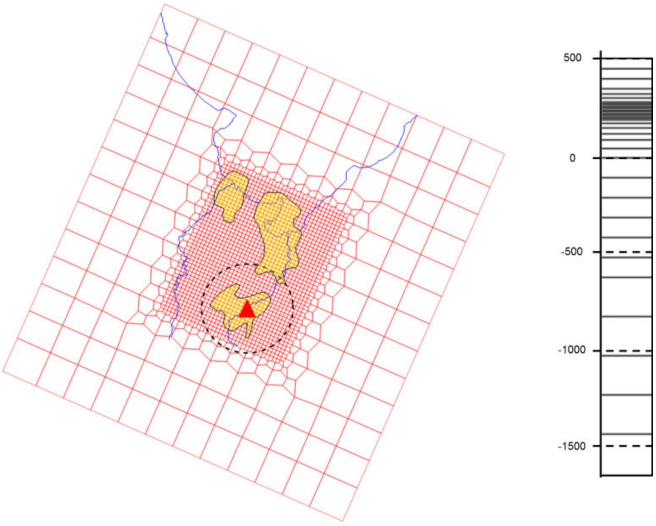

Fig. 3 Rotorua model grid with plan view and layer structure

For the RGS the model grid structure is shown in Fig. 3 with the edge of the lake indicated and the locations of the surface features highlighted. The key details of the grid are given in Table I. In particular note the very thin 5 m layers that were used in the layers where the surface features are found. For the topography satellite data was used to position the top of the surface blocks to the correct elevations and lake bathymetry was retrieved from International Lake Environment Committee Foundation (ILEC) where the model domain is below Lake Rotorua. Fig. 4 shows a comparison of the model topography with the actual surface elevation and it can be seen that a good representation has been achieved with the grid resolution used.

TABLE I
ROTORUA GRID PARAMETERS

| | |
|---|---|
| Grid area | 12.4 km × 18.3 km |
| Grid depth | 2,000 m |
| Blocks | 48,034 |
| Layers | 30 |
| Minimum block area | 125 m × 125 m |
| Minimum block height | 5 m |
| Orientation (angle to N-S) | 23.7° |

The equation of state that was selected was EWASG which allows AUTOUGH2 to solve for the transfer of heat, mass of water, mass of $CO_2$ and mass of chloride. By using this equation of state the model could be calibrated using information about $CO_2$ fluxes and chloride content. The shallow unsaturated zone is represented as a mixture of $CO_2$ and water rather than air and water which despite being physically incorrect still allows pressures and temperatures to be solved for accurately in the shallow zone.

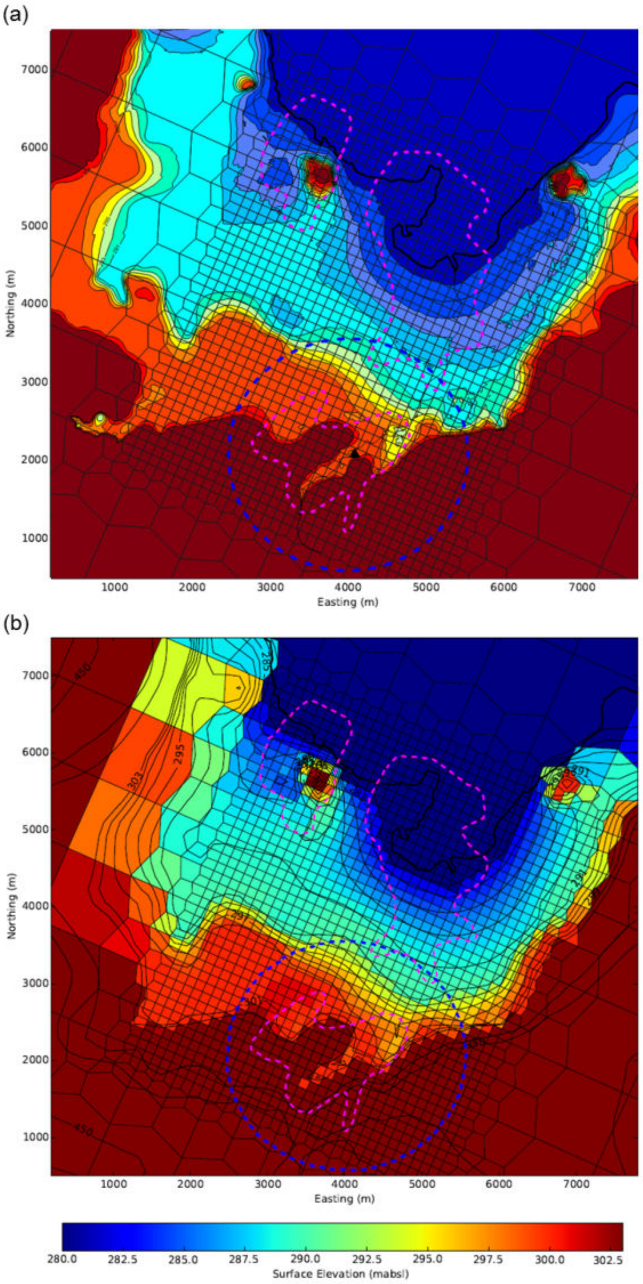

Fig. 4 Rotorua model surface topography (a) compared with the actual surface topography (b)

The permeability structure used in the model is shown for the layer at 100 masl in Fig. 5. It can be seen that the important faults and the geological formations are both represented explicitly in the model with different rock types. The high vertical resolution in the model also allows for the boundaries between geological formations to be captured accurately [19]. The values used for the permeabilities of the rock types in the best-calibrated model range from very permeable at 4.5 D down to very impermeable at 0.1 mD. These values were determined initially based on the geological formation and the fault structures and then adjusted during the model calibration process. Note that the permeabilities for each rock type were allowed to be anisotropic. This is important to allow the faults to act as pathways with a preferential direction for fluid flow.

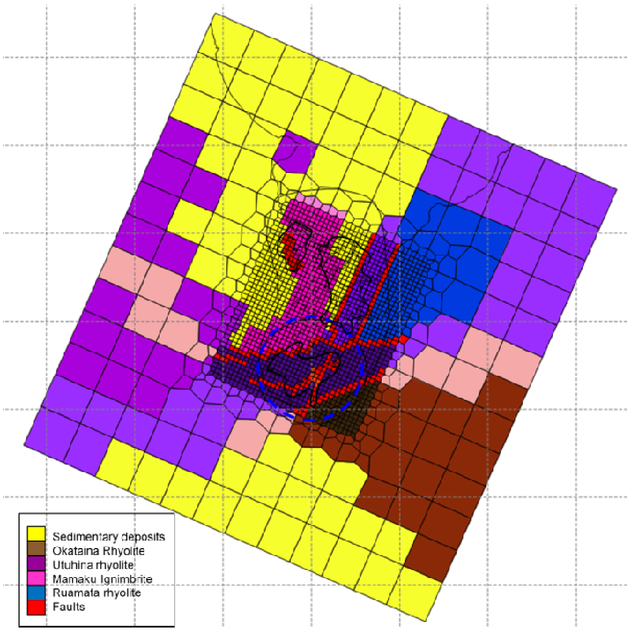

Fig. 5 Rotorua model permeability at 100 masl (approximately 200 m below the ground in the centre of the system)

The boundary conditions used for the model were consistent with standard practices for geothermal reservoir models [8]. The model domain was made large enough to include a sufficient area of meteoric recharge and to ensure that the lateral flows as the side boundaries were negligible. This allows the side boundaries to be treated as closed with no-flow conditions. For the top boundary except for the blocks beneath Lake Rotorua, atmospheric conditions were applied using atmosphere blocks which were connected to topography-following surface blocks. Meteroic recharge was injected into the blocks at a rate equivalent to the average local rainfall and infiltration rate. The infiltration rate used in blocks corresponding to the city centre was lower than elsewhere in the model to account for the high proportion of low permeability concrete and asphalt. For the blocks beneath Lake Rotorua no meteoric recharge was applied and wet atmosphere blocks were used with conditions equal to water at 10°C and a hydrostatic pressure calculated using an average lake surface of 280 masl.

At present it is beyond the capabilities of modelling tools to capture an entire geothermal convective system and also resolve the fine-scale effects near the surface [20]. As a result a certain amount of heat and mass must be injected into the bottom boundary of the model to represent the deep upflow. The amount of heat and mass injected is based on estimates from field data and its distribution is adjusted during the calibration process. For the Rotorua model 74300 t/day was injected into the base of the model at temperatures between 245° and 270°C. This agrees well with estimates for the RGS by [21]. The deep upflow was distributed mostly along the faults and concentrated around Kuirau Park, Ngapuna Stream and Whakarewarewa. The proportion of $CO_2$ and chloride in the deep upflow was also adjusted during the calibration process using estimates from geothermometers as guidelines.

More details of the Rotorua model and its development can be found in [19].

### C. Calibration and Results

The Rotorura model was calibrated in two stages. First, the natural state model was calibrated representing the RGS before significant utilization of the resource. Then a production history model was calibrated using information about the profile of historic utilization and the natural state model as the initial condition.

For the natural state model the simulations are run for an artificially long time until the system is at a steady state. The conditions are then compared with the available field data for the RGS before significant utilization occurred. The field data used in this calibration process includes:

- the location and extend of geothermal surface features
- estimates of mass flows rates for areas of surface activity
- inferred natural state reservoir temperatures and pressures

The plot in Fig. 6 shows the surface mass flow for the best calibrated natural state model. Comparing Fig. 6 with Fig. 2 shows that the model accurately represents the locations of the geothermal surface features within each of the main geothermal areas. Only two more quantitative estimates of the natural state mass flows of the RGS are available. The natural state heat flow from Whakarewarewa is inferred to be approximately 300 MW [15] the total heat flow for the main geothermal areas to be approximately 430 MW [14]. In the natural state model these quantities are 278 MW and 439 MW respectively, confirming the good match achieved.

The natural state reservoir pressures inferred by [15] are compared with those predicted by the model in Fig 7. It shows that although the model predicts the correct distribution, the pressures tend to be approximately 0.5 bar greater than the inferred values. This small discrepancy is most likely due to the model resolution as even with blocks of 5m thickness the position of the water table is only determined to within 5m corresponding to 0.5 bar of pressure.

The natural state temperatures were inferred by [13] using of data from boreholes drilled in the early stages of the utilization of the RGS as an energy resource.

Comparisons between the modelled temperatures and the inferred data for four representative boreholes are shown in Fig 8. More comparisons can be found in [19] but those presented in Fig. 8 demonstrate that the model is accurately representing the characteristics of the temperature plume in the shallow region. In particular the upflow profile in the Whakarewarewa area is reproduced, the outflows and inversions in both Ngapuna and Kuirau Park are captured and the cold lateral flow into central Ranolf Street area is predicted.

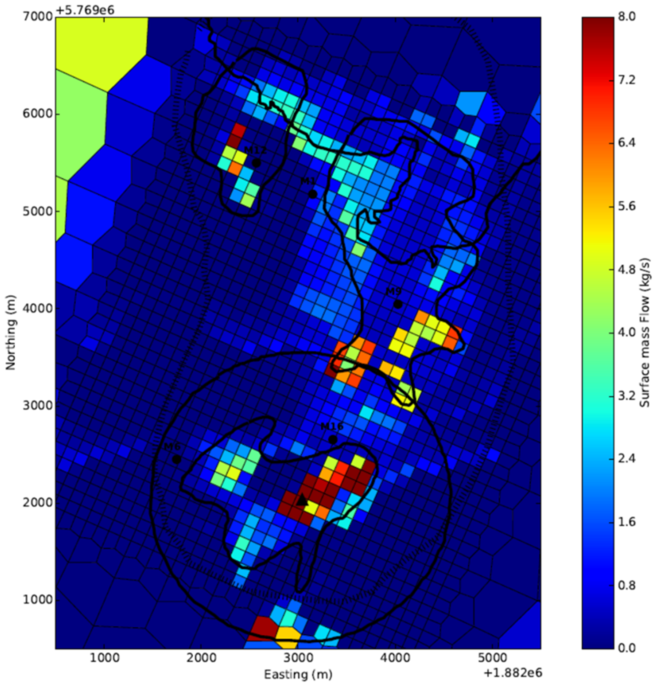

Fig. 6 Surface mass flow for the Natural state Rotorua model. Areas of geothermal surface features, monitor wells, the resistivity boundary and the exclusion zone are indicated

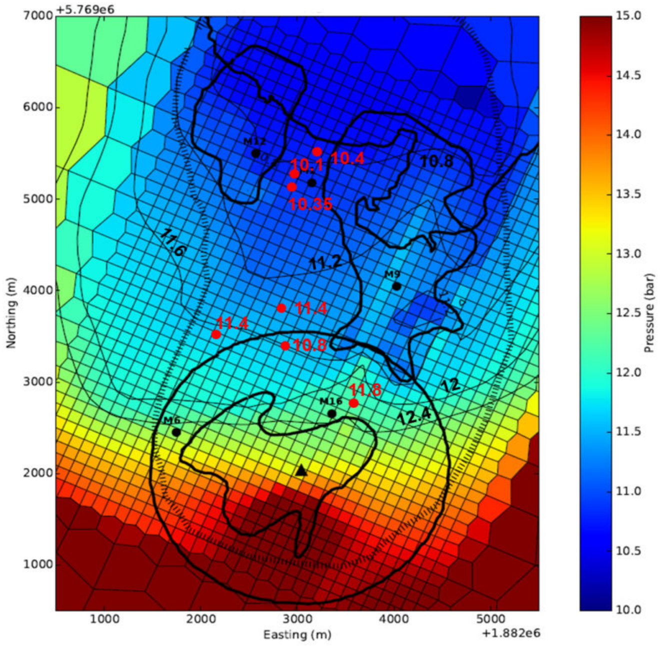

Fig. 7 Reservoir pressures from the natural state Rotorua model at 180 masl. Inferred field data from [15] shown in red

The production history simulations were carried out by running the model for an assigned period of time using the natural state results as the initial condition. During the simulation resource utilization was applied to the model that matched the historic records. Once the simulation was complete comparisons could be made between sets of data at different individual times during the simulation or transient sets of data for a particular quantity. Calibrating the model using these data ensures that the model parameters can correctly reproduce the RGS response to change.

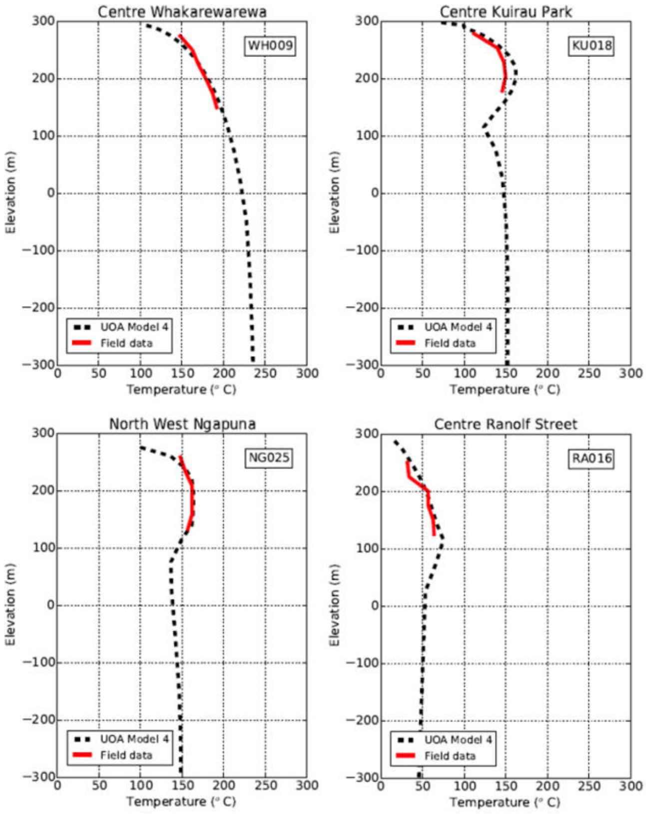

Fig. 8 Measured downhole temperatures in red compared with modelled temperatures in black for four representative wells in the Rotorua geothermal system

Because historic records of data are not complete or may be inaccurate, an exact utilization record is not available. However, total utilization and reinjection figures are available with some degree of accuracy and for the production history model these totals were distributed evenly amongst the known wells.

TABLE II
COMPARISON OF MEASURED AND MODELLED CHLORIDE CONCENTRATIONS IN ROTORUA (mg/kg)

| Location | Measured | Modelled |
|---|---|---|
| Ngapuna | 1683 | 1550 |
| | 13 | 41 |
| Whakarewarewa | 190 | 430 |
| | 959 | 1000 |
| | 756 | 698 |
| | 512 | 531 |
| Rhyolite dome | 303 | 306 |
| | 460 | 740 |
| Kuirau Park | 338 | 350 |

In reality a number of unsanctioned and unrecorded wells also existed but as the results of the comparisons show, the estimated historic utilization is sufficient to produce very good matches between the model results and the field data. For

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more details on the historic utilization refer to [19] and the references therein.

Table shows the very good match achieved between the chloride concentrations recorded by [22] in 1983-84 and those predicted by the model for the same time. This gives a high degree of confidence in the ability of the model to predict chloride concentrations in the RGS in the future.

Similarly the plots in Fig. 9 comparing the measured and modelled $CO_2$ fluxes in 2003 show that the model does a very good job of reproducing the behaviour of the real system. Both chloride and $CO_2$ not only contribute to the chemistry of geothermal surface features but they also affect the thermodynamic properties of the geothermal fluid which in turn plays a crucial role in their behaviour.

The final results presented for the RGS compare transient pressure data recorded in two monitoring wells with the model predictions. The locations of the monitoring wells are shown in Fig. 2. The transient pressure comparison is shown in Fig. 10 and covers the full period of the production history simulation. The date of the borehole closure programme is indicated with a dashed line and the sharp recovery in both the measured and modelled pressures is evident. For monitoring well M9 the match is very good for both the pressure decline as a result of utilization and the recovery. For M16 the model slightly under predicts the decline and then over predicts the rate of recovery.

## III. Case Study Two – Orakei-korako

### A. Description of the system

The OGS is a protected geothermal system with numerous important geothermal features. From Fig. 1 it can be seen that the OGS lies between the Ngatamariki and Te Kopia geothermal systems both of which are currently being utilized for electricity production. While differences in the ionic concentrations of the geothermal fluid suggest that there is no direct link between the systems, nevertheless monitoring programs have been initiated to detect any interaction that may occur.

The most common geological formations observed at the surface of the OGS are siliceous sinter deposits, Pleistocene lake sediments such as the Huka Falls and Waiora Formations, Quaternary ignimbrites and rhyolites, and alluvial matter such as the Hinuera Formation and Taupo Pumice Alluvium [23]. While these formations are typical of the TVZ the OGS is unusual because drilling logs from shallow wells do not contain any evidence of the low permeability capping formations found in other systems such as Wairakei [24] and Ngatamariki [25], [26].

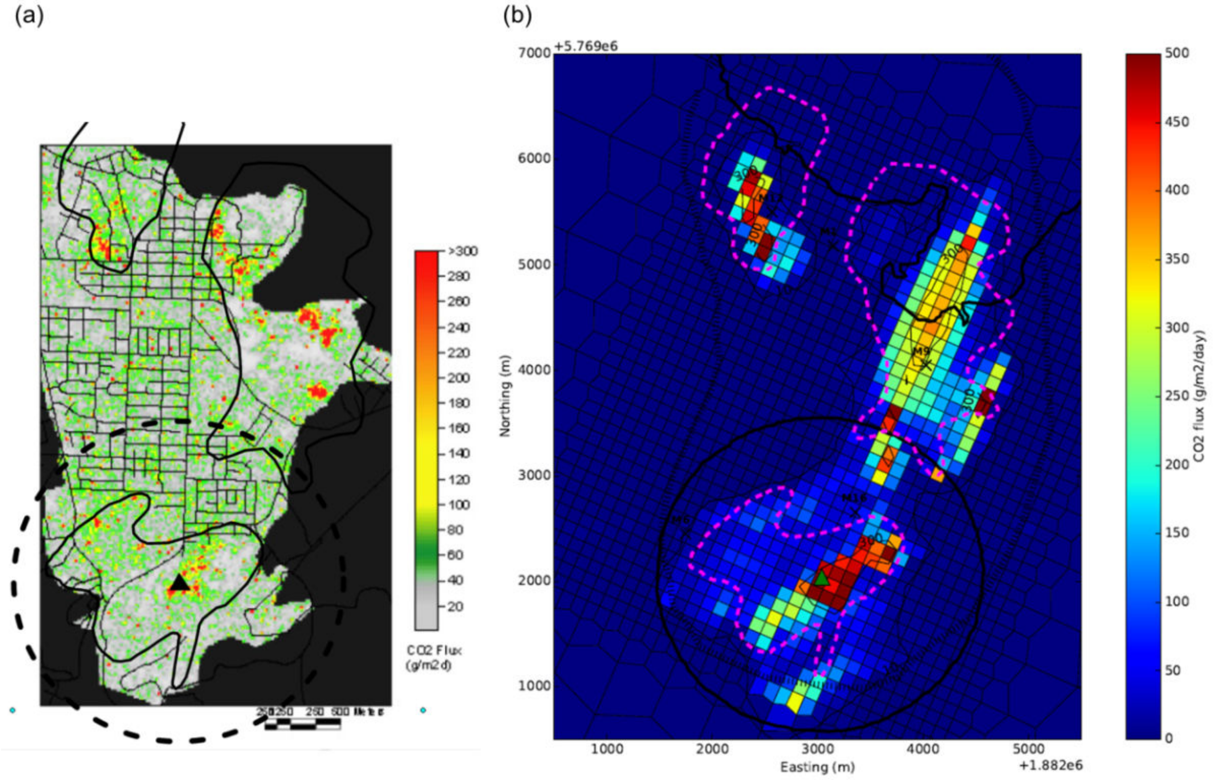


Fig. 9 Comparison of CO2 flux measurements for the Rotorua geothermal system in 2003. Measured data from [16] shown in plot (a) and modelled results in plot (b)

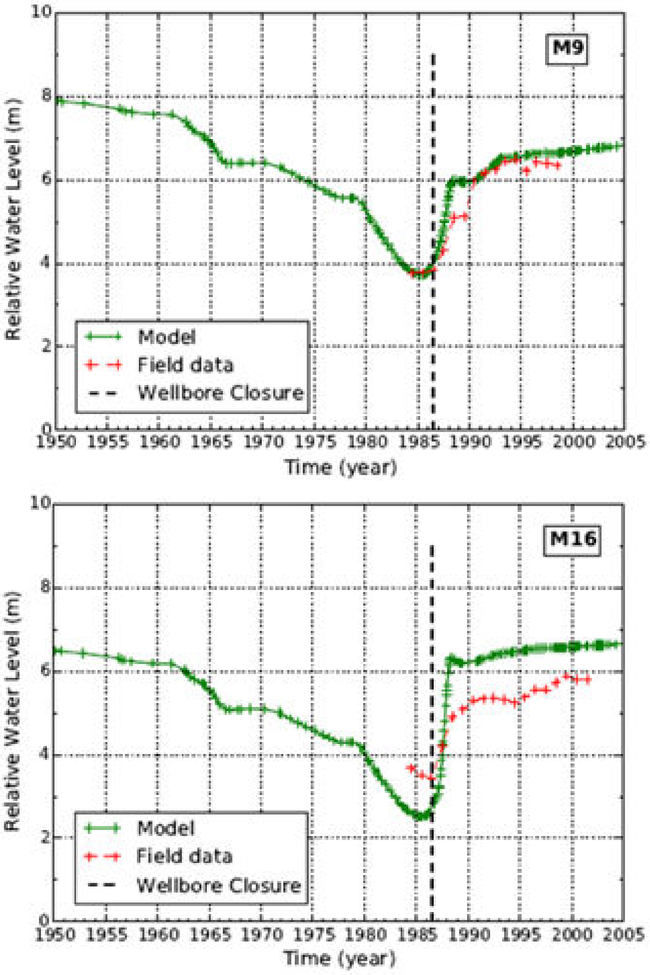


Fig. 10 Comparison of measurements of relative water levels in two monitoring wells with modelled results for the Rotorua geothermal system

The large number of faults and fault intersections provide numerous pathways to the surface and the lack of a capping formation means that high flow rates and large geothermal surface features are abundant in the OGS. The total heat output is estimated to approximately 340 MW and apart from the geothermal surface features a large amount of geothermal fluid seeps into the Waikato River which flows through the system. Reservoir temperatures of 278°C have been estimated using geothermometers [26] and the maximum temperature encountered in the four deep wells drilled in the OGS were 265°C [28].

Despite the drilling of four deep wells from 1964 to 1965, the OGS has never been utilized for energy production and is now completely protected. However, during the geological survey carried out by [23] extensive field data was collected regarding the geothermal surface features including information from over 1000 springs and surface heat flux measurements for the entire thermally active zone.

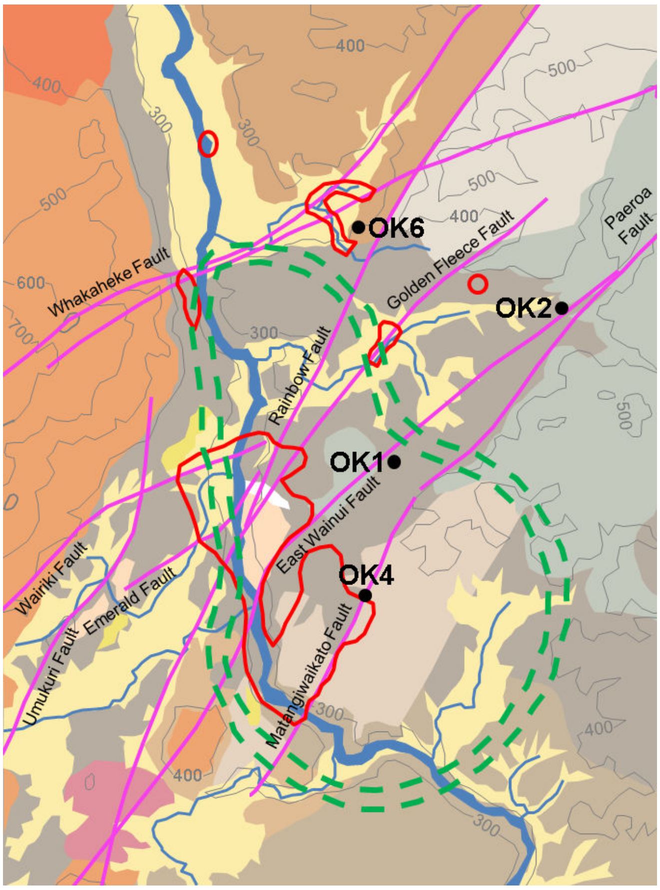


Fig. 11 Map of Orakei-korako showing the surface features (red), geothermal wells, major faults (magenta) and the resistivity boundary (green). Surface geology and topography are also shown

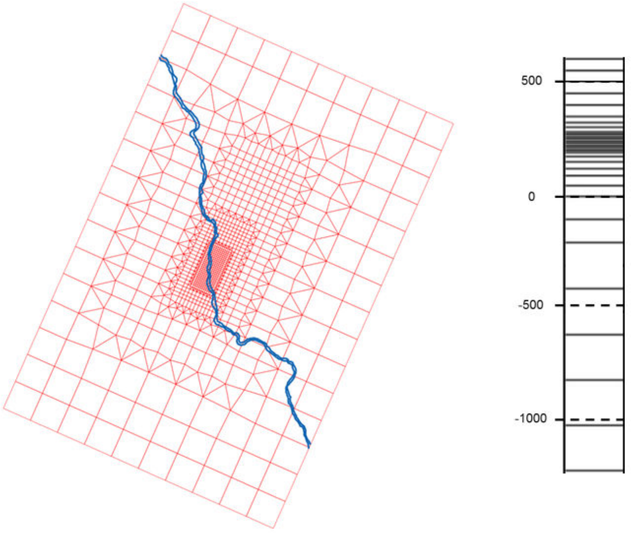


Fig. 12 Orakei-korako model grid with plan view and layer structure

### *B. Model Setup*

The model of the OGS was set up in the same manner as the model of the RGS. Small blocks and thin layers were used to give high resolution in areas where the geothermal surface features are found. The grid for the OGS model is shown in

Fig. 12 and the parameters are given in Table III. Like the RGS model the OGS model is rotated to align the grid with the major faults, allowing them to be represented more accurately using anisotopic permeabilities. Also, the tops of each surface block have again been fitted to satellite data for the area ensuring that the model accurately represents the surface topography. Unlike the RGS model, the air-water equation of state was used meaning that the shallow unsaturated zone is correctly represented but the movement of important chemical species is not.

As Fig. 13 shows all the available data regarding the geological formations shown in Fig. 11 was used to generate the model geology. Also, information from the four well logs was combined with data from nearby systems and knowledge of the geological processes that occurred in the TVZ to populate the model geology at the deeper elevations [27].

TABLE III
ORAKEI-KORAKO GRID PARAMETERS

| | |
|---|---|
| Grid area | 8 km × 12 km |
| Grid depth | 1,900 m |
| Blocks | 21,756 |
| Layers | 22 |
| Minimum block area | 50 m × 50 m |
| Minimum block height | 10 m |
| Orientation (angle to N-S) | 24° |

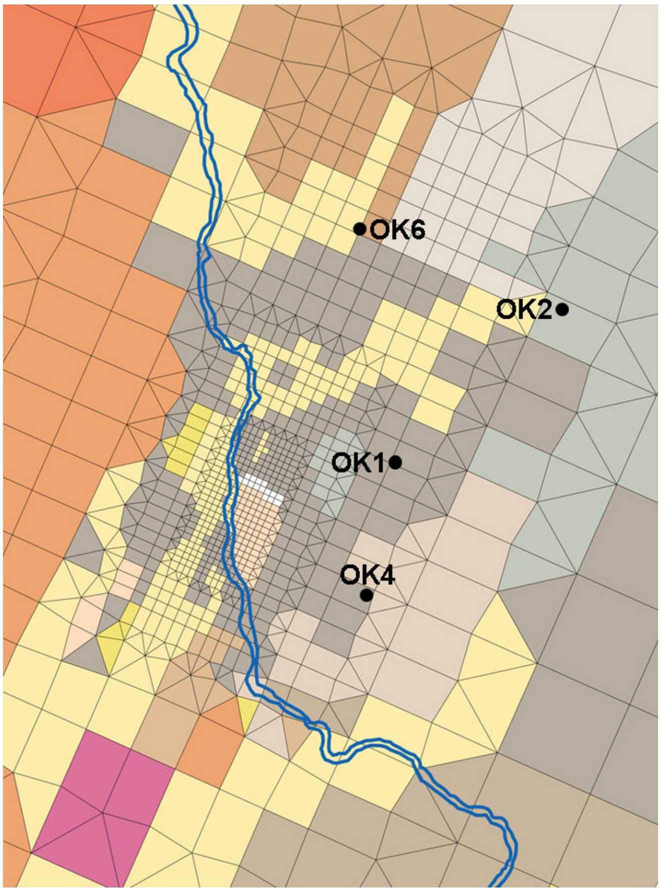


Fig. 13 Orakei-korako model surface geology

In Fig 14 the vertical permeabilities are given shown for the bottom layer of the model at -1500 masl. As with the RGS model all of the important faults are represented explicitly in the model with different rock types. The values used for the permeabilities of the rock types in the best-calibrated model range from very permeable at 2 D down to very impermeable at 0.1 mD. These values were determined initially based on the geological formation and the fault structures and then adjusted during the model calibration process.

Once again closed lateral boundary conditions were used as the model domain was designed to be large enough to encompass the entire OGS and its meteoric recharge area. The boundary conditions at the top of the model were applied in the same manner as for the RGS model with one type of atmosphere block for dry land and another for representing the influence of the Waikato River.

High infiltration rates have been estimated for this region of the Waikato ranging between 22% and 44% [29]. In the model an infiltration rate of 30% was used and applied to an average rainfall of 1500 mm/yr for the Orakeikorako area corresponding to the injection of $1.43\text{x}10^{-5}$ kg/m$^2$s of cold water into the surface blocks of the model that are not beneath the Waikato River.

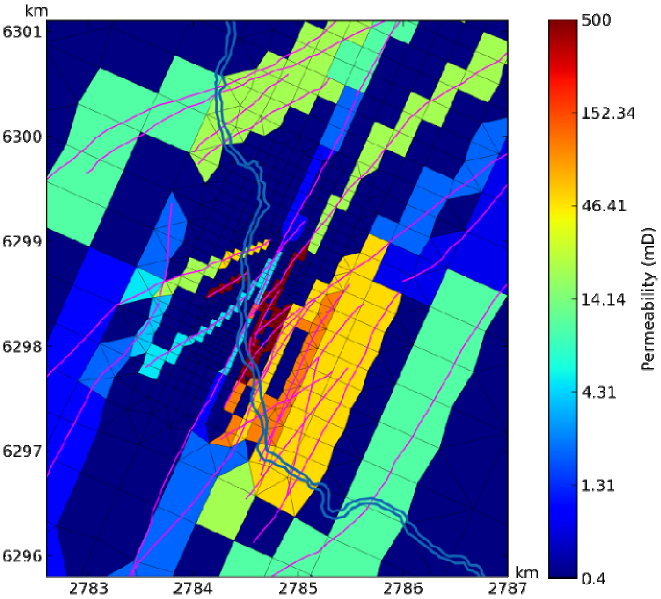


Fig. 14 Orakei-korako model permeability at -1500 masl

At the bottom boundary of the model 262.1 kg/s of fluid were injected with an average enthalpy of 1005 kJ/kg to represent the deep upflow in the system. This gave a total heat input from deep sources of 264 MW which is lower but still comparable to the estimate given by [23] of 342 MW.

Finally, the numerous hot springs in the OGS were represented in the model using wells on deliverability. This approach has been used previously [30], [31] and allows each spring to be calibrated to its corresponding field data. While this approach is considerably more time-consuming than the approach used in the RGS it allows direct comparisons to be made with the limited field data available for the OGS.

International Science Index, Mechanical and Mechatronics Engineering Vol:9, No:3, 2015 waset.org/Publication/10000647

For more detailed information regarding the model setup please refer to [27].

### *C. Calibration and Results*

The model of the OGS was calibrated in the same manner as the model of the RGS with the exception that only a natural state model has been fully calibrated. This is because although a monitoring programme of the OGS has been ongoing [32] there is still a limited amount of field data that records transient quantities.

For the OGS the most important calibration data was the surface heat flow at warm and steaming ground. The model results are compared with the field data in Fig. 15.

Fig. 15 shows that the model reproduces the surface heat fluxes very well giving a high level of confidence in the ability of the model to predict the long term behaviour of the geothermal surface features.

Also used for calibration were the mass flows and temperatures of over 1000 springs and the measured and interpreted water table levels. In both cases good agreements were achieved and the results are given in detail in [27]. The agreement between model and the field data for the springs is important as this ensures that the natural states of these surface features are accurately represented. Matching the water table levels is also important as it controls the behaviour of many of the surface features.

Unlike RGS, the temperature profiles for the four deep wells were able to be used to more accurately calibrate the deep zones of the OGS model. The measured and modelled downhole temperatures are compared in Fig. 16 for each of the deep geothermal wells. In plots (a)-(d) the model reproduces all of the important features of the data including cold inflows, deep hot outflows and small shallow inversions. Plot (b) shows that the deep features of the data are reproduced but not the shallow ones. Closer inspection of Fig. 13 will show that well OK2 is located in a large, low resolution block several km from the main geothermal area and to achieve a better match the more refined region of the model would need to extend out to this area. In general, the matches with the deep geothermal well temperatures ensure that the deep part of the OGS is represented accurately. This is important as the deep geothermal resource is the driving force for the surface features.

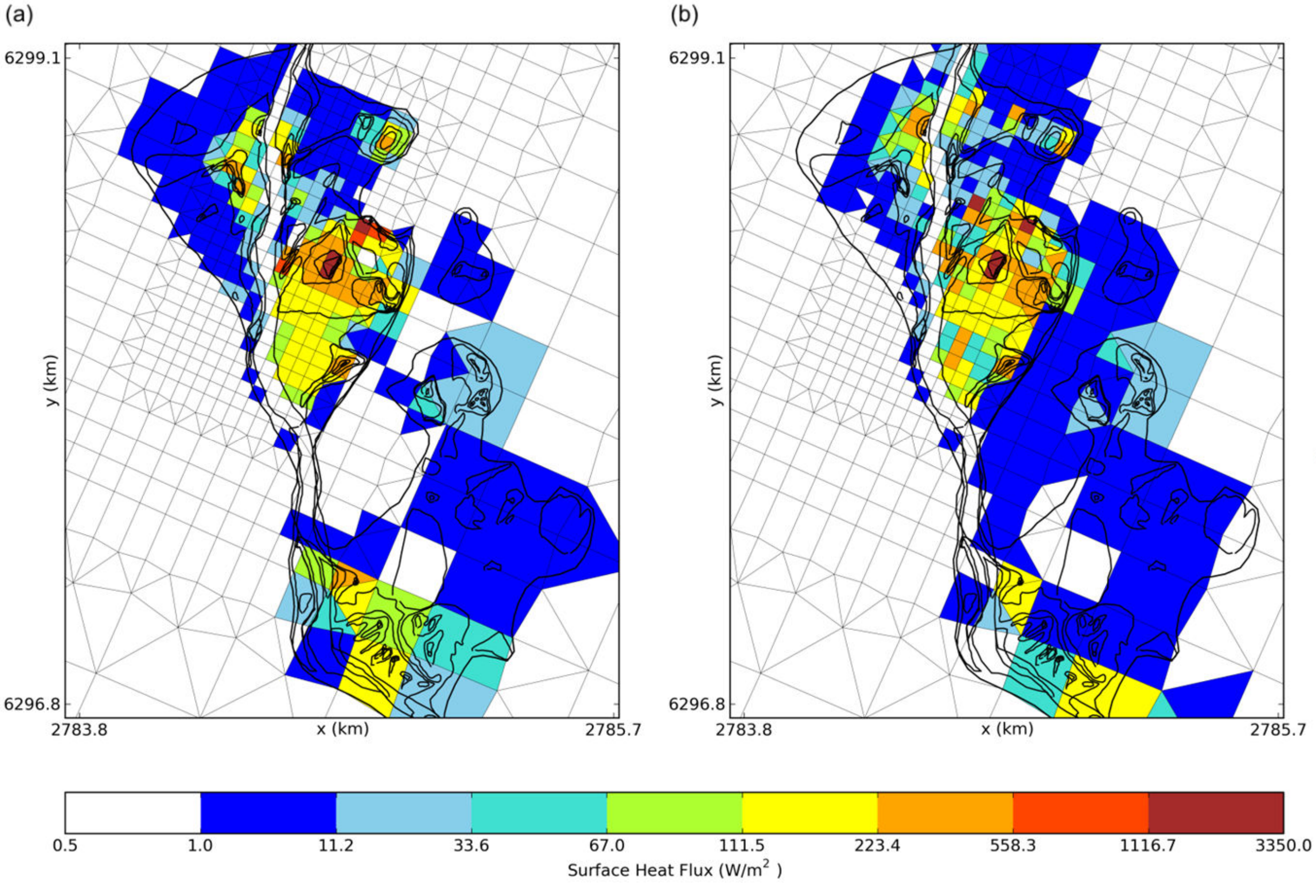
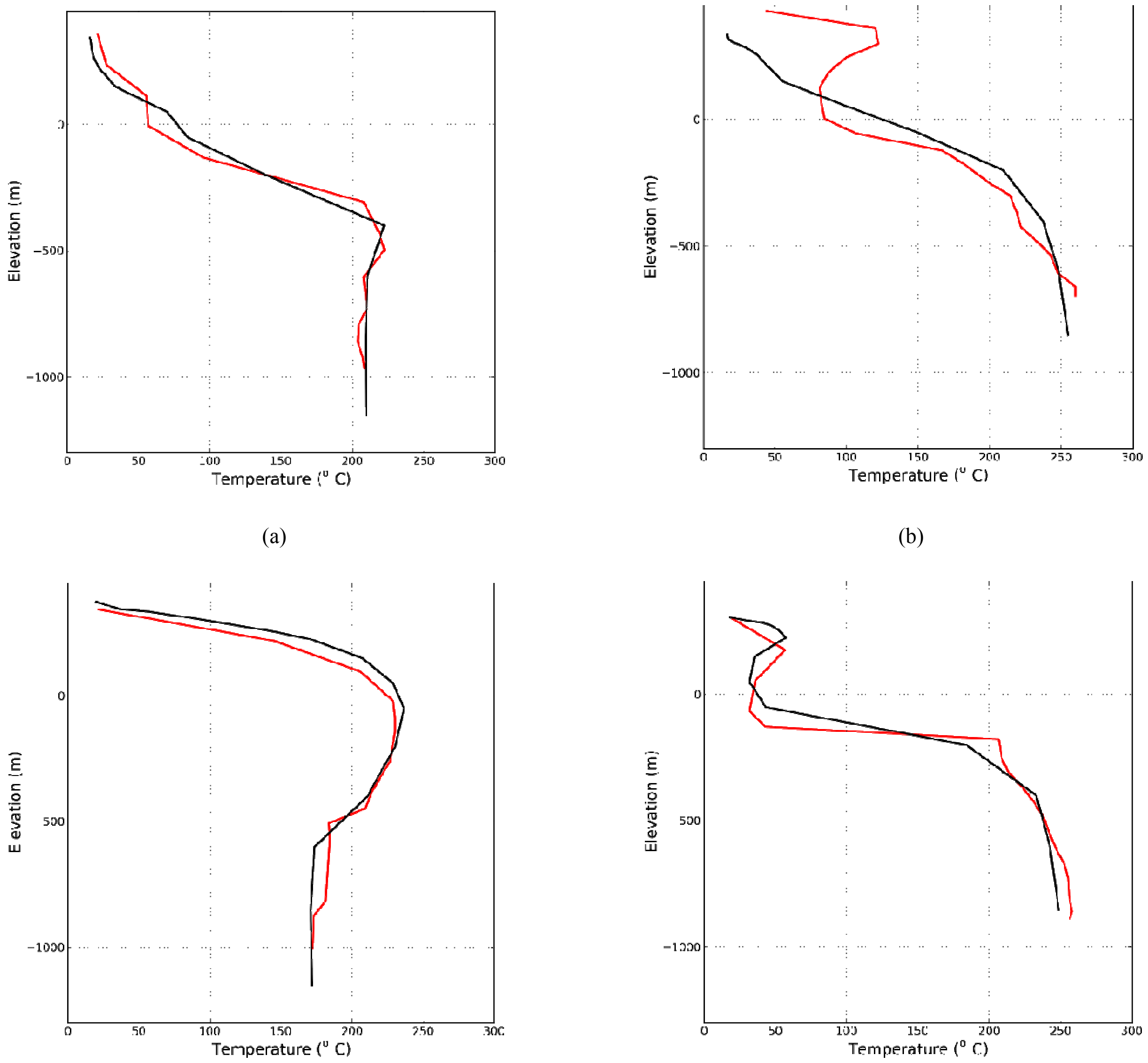


Fig. 15 Surface heat flux at Orakei-korako at warm and steaming ground Processed measured field data (a) compared with model predictions (b). Contours from [23] shown as black lines



(a)

(b)

(c)

(d)

Fig. 16 Comparison of measured (red line) and modelled (black line) downhole temperatures at (a) OK1, (b) OK2, (c) OK4 and (d) OK6. Refer to Fig. 11 for the locations of the wells

## IV. CONCLUSIONS

Approaches have been presented for developing and calibrating numerical geothermal reservoir models that are capable of accurately representing geothermal surface features. The approaches were discussed in the context of cases studies of the Rotorua geothermal system and the Orakei-korako geothermal system, both of which contain important surface features. The results show that models are able to match the available field data accurately and hence can be used as valuable tools for predicting the future response of the systems to change. Work has already begun to include more important effects such as variable climatic conditions and different chemistry. More data, particularly transient data for the OGS is being collected and will be used to further calibrate the model. The government agencies responsible for monitoring, managing and protecting the geothermal systems are already collaborating with the authors to integrate the models into their programs.

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