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# An Updated Numerical Model of Rotorua Geothermal Field

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## ABSTRACT

The Rotorua geothermal field is situated at the southern margin of the Rotorua Caldera in the Taupo Volcanic Zone, New Zealand. The Rotorua system lies beneath a major city and has a unique abundance of natural features of great cultural, economic and scientific value. However from the 1950's onwards, intensive extraction of fluid and heat from over 900 shallow wells for commercial and industrial purposes, mainly heating and bathing, resulted in a decline of the surface features. In 1986, a bore closure program was enforced and geyser activity and hot springs have rejuvenated progressively with some springs overflowing recently for the first time in over 30 years.

A three-dimensional numerical model of the Rotorua system has been developed to study the response of surface features to production and reinjection, called here UOA Model 3. UOA Model 3 differs from previous models by having a much finer layer structure in the shallow zone and the inclusion of an unsaturated zone. This enables a better representation of near-surface mass and heat flow behaviour. UOA Model 3 also includes the complex structural and lithological structures associated with Rotorua's asymmetrical caldera collapse setting. The model has been calibrated against a large number of shallow temperatures, the locations and magnitudes of surface activity and available pressure transients.

## 1. INTRODUCTION

The Rotorua Geothermal Field (RGF) underlies much of Rotorua city, New Zealand with surface geothermal activity confined to three areas: Whakarewarewa/Arikikapakapa in the south, Kuirau Park/Ohinemutu to the northwest and Government Gardens/Sulphur Bay/Ngapuna to the north (Figure 1).

The RGF is unique in that it lies beneath a major city and contains one of New Zealand's last remaining areas of major geyser activity at Whakarewarewa (Figure 1). These features hold a strong cultural significance (Māori beliefs and customs) (Neilson et al., 2010), economic value as tourist attractions and energy sources, and remarkable biodiversity (Acland, 2006).

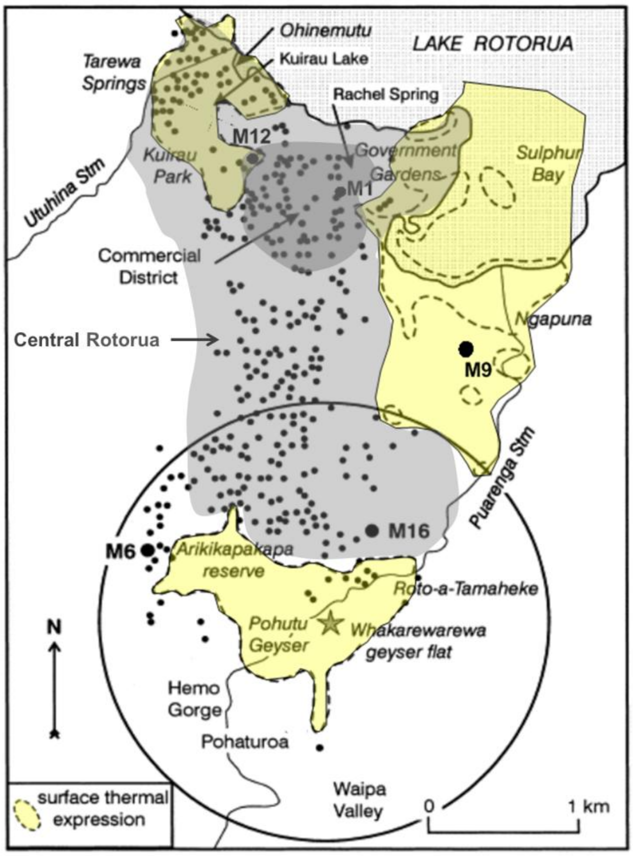



**Figure 1: Surface features and distribution of geothermal and monitoring wells in Rotorua city in 1985 (From Scott and Cody 2000)**

Exploitation of the geothermal heat began with traditional use which was followed by a phase of intensive geothermal fluid abstraction from shallow bores. During the latter, lack of regulations led to an erratic development of the field and, in the late 1970's a significant decline in surface geothermal activity was observed (Gordon et al., 2005). Increasing concern over the effect of geothermal fluid withdrawal on springs and geysers led to the closure of all bores within a 1.5 km radius of Pohutu Geyser (Whakarewarewa), closure of all government department wells in Rotorua City and introduction of a royalty scheme to promote fluid reinjection into the reservoir rather than discharge to shallow soakage (Gordon et al., 2005). These historic time periods are generally defined as:

- Traditional use and natural state -1800's to 1950;
- Intensive extraction of fluid and heat - 1950 to 1986;
- Bore closure and post closure field recovery phase - 1986 to 2014;

Previously numerical models have been developed to simulate the field behavior and match the pressure drawdown and recovery of a few monitoring wells (Burnell and Kissling 2005) but they were relatively coarse and of low resolution in the shallow zone.

The model discussed in the present paper aims to describe the RGF with greater precision and is calibrated against more observations (pressure, temperature, surface mass and heat flow). The model has a much finer horizontal and vertical structure which allow representation of the complex geology and the near-surface flow and surface discharge, which is the main area of interest for the Rotorua field.

## 2. GEOLOGICAL SETTING

Rotorua city lies within the Taupo Volcanic Zone (TVZ) in the North Island of New Zealand (Figure 2). The TVZ is a volcano-tectonic depression dominated by Quaternary rhyolitic and andesitic volcanism in which major extensional faults strike SW-NE. Accompanying the high volcanic activity is an extremely high natural heat flow, inducing large convective cells of hot rising fluid which give rise to the geothermal fields. The occurrence of surface features and resistivity surveys have delineated more than 20 geothermal fields within the TVZ, one of which is the RGF (Figure 2).

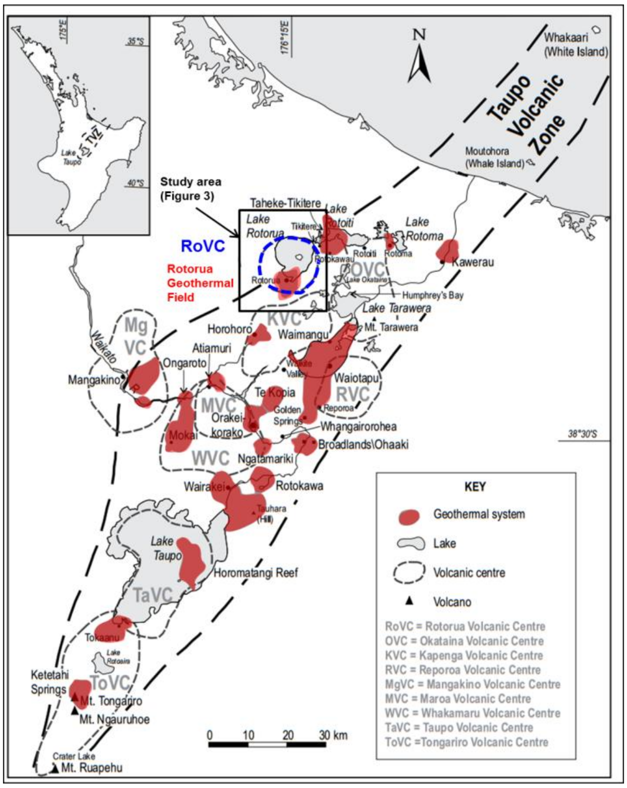



**Figure 2: Location of the RGF (in red) within the Rotorua Caldera (in blue) (From Cody, 2007)**

The RGF covers an area of approximately 18-28 km$^2$ as defined by electrical resistivity surveys (Bibby et al., 1992). It is located within the Rotorua rhyolitic volcanic centre at the southern margin of Lake Rotorua. A simplified geological timeline of the formation of the caldera can be summarized as follows (Ashwell et al., 2013):

- <u>240-200ka:</u> A single cataclysmic eruption event which resulted in the deposition of an extensive ignimbrite sheet, the Mamaku Ignimbrite (mauve in Figure 3).
  The ignimbrite extrusion led to an asymmetrical multiple block caldera collapse syn-eruption.
- <u>200ka:</u> Dike-fed lava domes eruptions (Utuhina Group) using pre-existing faults (purple in Figure 3).
- <u>200-60ka:</u> Filling of the caldera with water. Changes in lake levels left several terraces (tephra and alluvial sediments) across the Utuhina domes and Mamaku Ignimbrite: commonly called the Rotorua Sediment sequence (yellow in Figure 3).

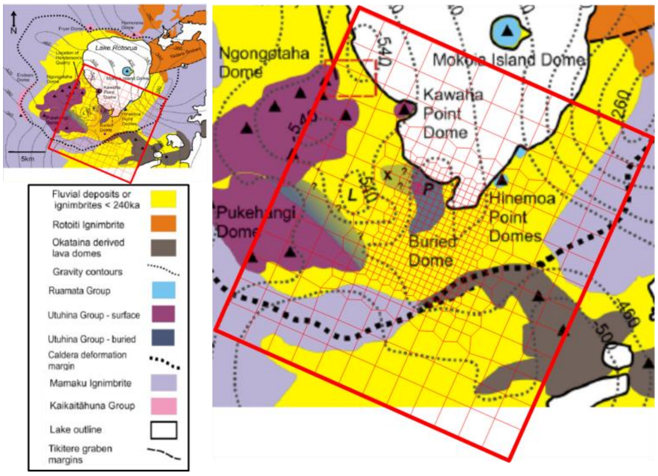



**Figure 3: Geological map of the Rotorua Caldera, gravity anomaly contours (µN/kg) (Ashwell et al., 2013). Model grid shown in red.**

Although there is a lack of surface structures in the Rotorua Caldera, studies of the morphology of the caldera (centered on a gravity anomaly to the northwest of the city) (Figure 3) and orientation of preserved lava domes reveals four major faultings trends:

- SW-NE: Regional extension
- NW-SE: NW–SE basement faults orthogonal to the main rift strikes, apparent from the pronounced offset of each segment across the transfer zones (attributed to reactivated basement structures) (Ashwell et al., 2013).
- N-S: Flow banding within rhyolitic Domes suggests near N–S orientated faults. They are associated with caldera collapse structures that linked extensional and basement structures at depth (Ashwell et al., 2013).
- Ring Fault: Inner caldera boundary fault: caldera-forming fault (Wood, 1985).

Knowledge of these three lithologies and orientation of the faults are essential for understanding the controls of the flow system within the Rotorua geothermal system which will be discussed in the following section.

## 3. CONCEPTUAL MODEL

Prior to the wellbore closure, an important amount of data regarding wells and springs (lithology, temperature, pressure, feedzone/flow rate, fluid composition, etc.) of the Rotorua field was collected as part of the Rotorua Geothermal Monitoring Programme. Despite the large number of wells (several hundred) most are less than 300m deep. There is, therefore, a very large amount of data available only for shallow part of the field. Nonetheless from the following observations, a conceptual model accounting for the key features governing the flow of the RGF was built:

- Feedzones of the production wellbores are located within the Rotorua Rhyolite Dome (Buried Dome) and the Mamaku Ignimbrite and contains respectively:
  - Sub-boiling, medium chloride and bicarbonate concentration fluid (≈400 mg/kg). The upper part consists of pumiceous, brecciated and fractured rhyolite of high permeability (Wood, 1992).
  - Boiling, high enthalpy, high-chloride fluid (≈1000 mg/kg). This zone shows good fracture permeability (Wood, 1992).

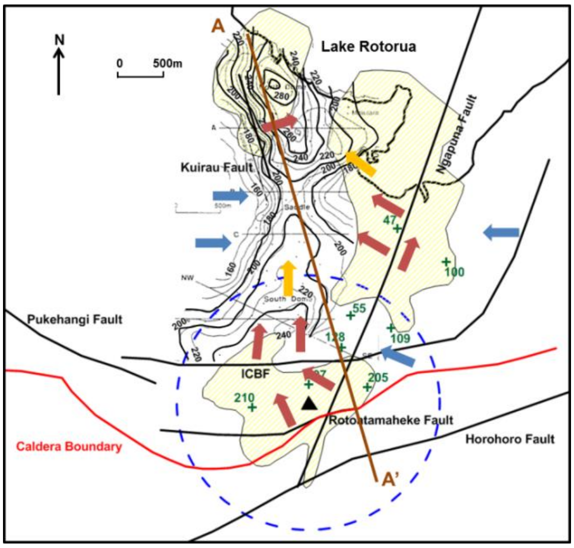



**Figure 4: Geological and structural setting of the RGF**

- Both formations are overlaid by the Rotorua Sediment sequence of low vertical permeability that acts as an aquitard and confines the geothermal fluid.
- Well/spring chemistry (chloride, Bicarbonates) and temperature have highlighted three upflow zones; along Puarenga Stream, Whakarewarewa and Kuirau Park (Giggenbach and Glover, 1992). They correspond closely to faults associated with caldera collapse mechanisms (section 2) and where depth discrepancies (linked to downfaulting) in the top of the Mamaku Ignimbrite were observed (Figure 4). These structures are believed to provide permeable paths for the rising geothermal fluid.
- Wells within the Buried Dome show a temperature inversion, suggesting lateral fluid flow (Wood, 1992). Fluid moves laterally from the faults within the Ignimbrite sheet and the rhyolite domes to the north from Whakarewarewa and westward from Ngapuna Fault and mixes with cold groundwater (Figure 5).

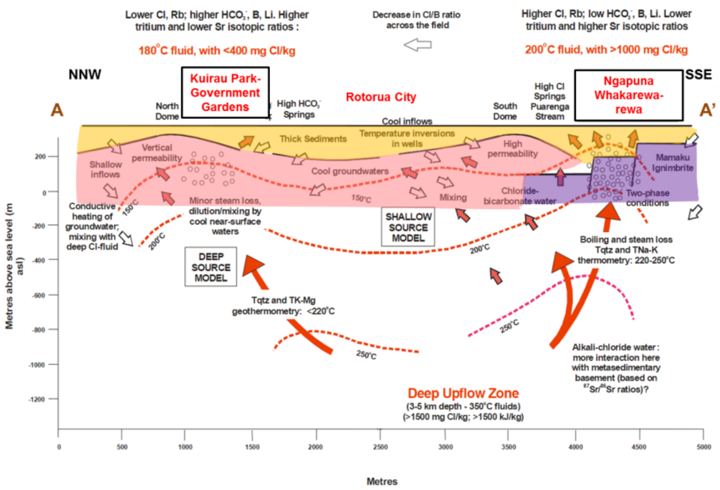



**Figure 5: Cross section of the RGF conceptual model (location highlighted in Figure 4) (From Gordon et al., 2005)**

## 4. COMPUTER MODELLING

Computer modeling alongside with an extensive monitoring programme is one of the key tools for understanding and predicting the behavior of the RGF. The first numerical model was developed in the 1980's and was used to assess the likely effects of the bore closure program. Its conclusions supported the implementation of such a programme (Grant *et al*., 1985). Since that time, modelers from Industrial Research Limited (IRL) have set up two computer models, the first in the 1992 (Burnell and Young, 1992) and the second in the 2005 (Burnell and Kissling, 2005).

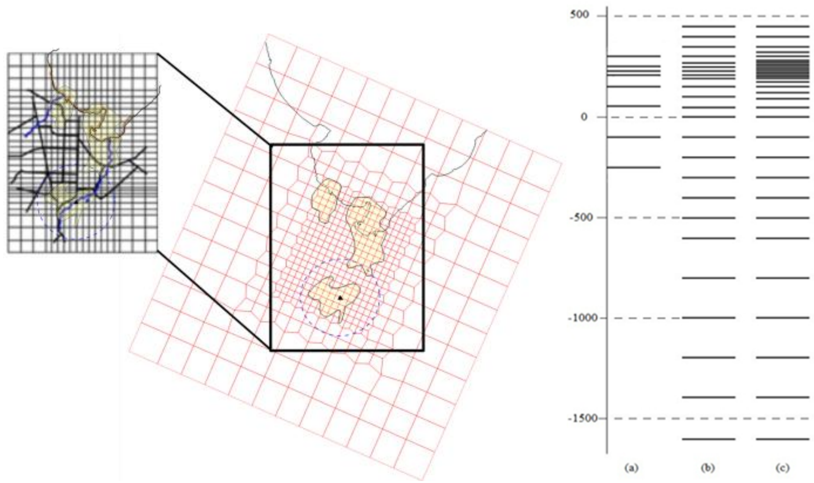



**Figure 6: 1. Grid layout for IRL model 2 and UOA Model 3 and layer structure for IRL Model 2 (a), UOA Model 3 (b) and proposed grid for UOA Model 4 (c).**

The current model is different from previous models in the following respects:

- It covers a larger area and extends to a greater depth (Figure 6).
- It is rotated to line up with the major structures (Buried Dome, Ngapuna Fault) (Figure 6).
- It has an irregular grid with a finer layer structure (Figure 6).
- The shallow unsaturated zone and the topography are incorporated.
- The complex caldera collapse structures are included: explicit faults, down-faulting of the Mamaku Ignimbrite, contour of Rhyolite dome as shown in Figure 4 (Figure 7)

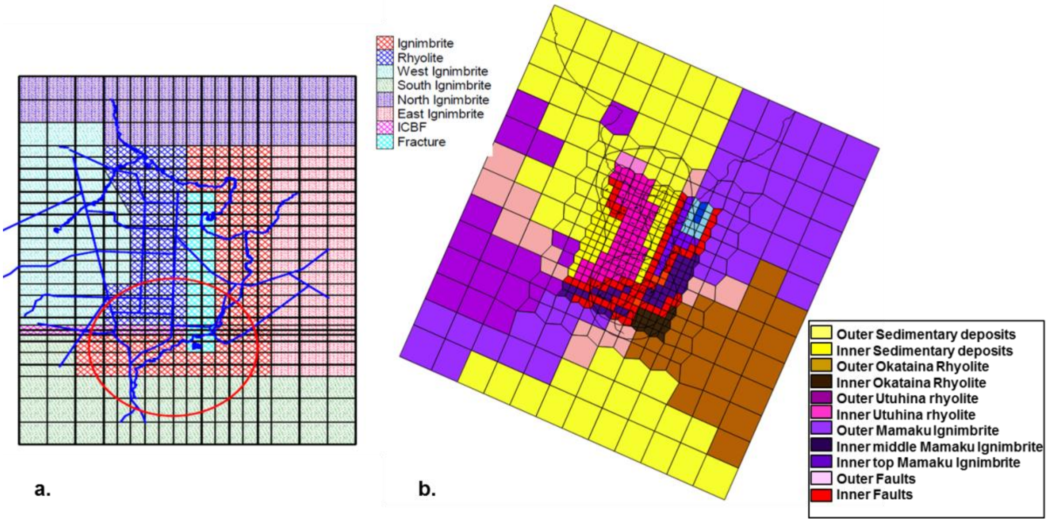



**Figure 7: Geological settings at 100 masl (IRL 2005 and UOA Model 3)**

A comparison of some of the model parameters is given in Table 1.

**Table 1: Summary of differences in the models of Rotorua Geothermal Field**

| Category | UOA Model 3 | IRL Model 2 |
|---|---|---|
| Grid area | 12.4 km x 18.3 km | 6 km x 8.5 km |
| Grid depth | 2,000 m | 570 m |
| Blocks | 11,302 | 3,550 |
| Orientation (angle to N-S) | $23.7^0$ | $0^0$ |
| Rainfall rate | 1 m/year | 1.3 m/year |
| Infiltration rate | 10% | 7.5% |
| Layers | 23 | 7 |
| Surface | Follows topography & lake bathymetry | Planar water table, 40m lower at the lake |
| Equation of State (EOS) | 4 (air + water) | 1 (pure water + chloride tracer) |

The main objective of this model is to provide a more detailed representation of the shallow zone at Rotorua. This led to the implementation of a fine layer structure, thus enabling the modeling of the very shallow unsaturated zone which in turn requires the use of air/water equation-of-state (EOS4) in the numerical simulator AUTOUGH2 (Yeh *et al*., 2012), the University of Auckland's version of TOUGH2 (Pruess, 1991).

## 5. BOUNDARY CONDITIONS

**Top boundary**: Atmospheric conditions are assigned at the top surface (1 bar, $15^0$C). Below the lake surface, the pressure is set to the hydrostatic pressure corresponding to the depth of the lake assuming a water temperature of $10^0$C. The bathymetry of the lake was retrieved from International Lake Environment Committee Foundation (ILEC). And the mean water level of 280 mRL for Lake Rotorua was sourced from BoPRC (2013).

An annual rainfall of 1,000 mm/year and an infiltration rate of 10% are used. It is represented by cold water injected into the top of the model.

Combining the topography information and Lake Rotorua bathymetry, the surface elevation of the model was fitted to the data using pyTOUGH (Croucher, 2011) (Figure 8).

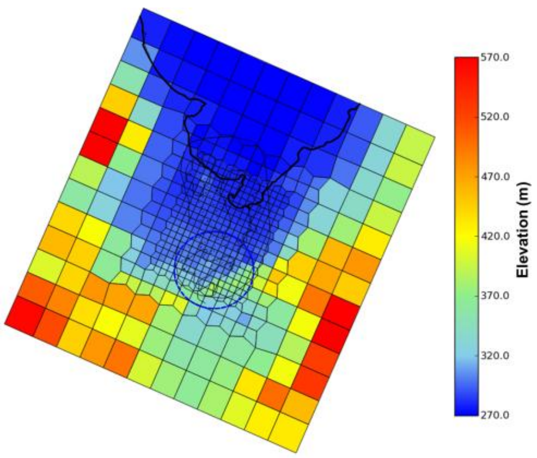



**Figure 8: Surface elevation of UOA Model 3.**

**Side boundaries**: All the side boundaries are assumed to be closed; i.e. no heat or mass coming into or going out of the system. The side boundaries are located sufficiently far from the active system for this approximation to be valid.

**Base boundary**: Inflow of high enthalpy water up the inferred faults (Table 2) and a conductive flow of heat of 80 mW/m$^2$ is applied elsewhere. A comparison of the deep inflow of hot water used in UOA Model 3 and IRL Model 2 (Burnell and Kissling, 2005) is given in Table 2.

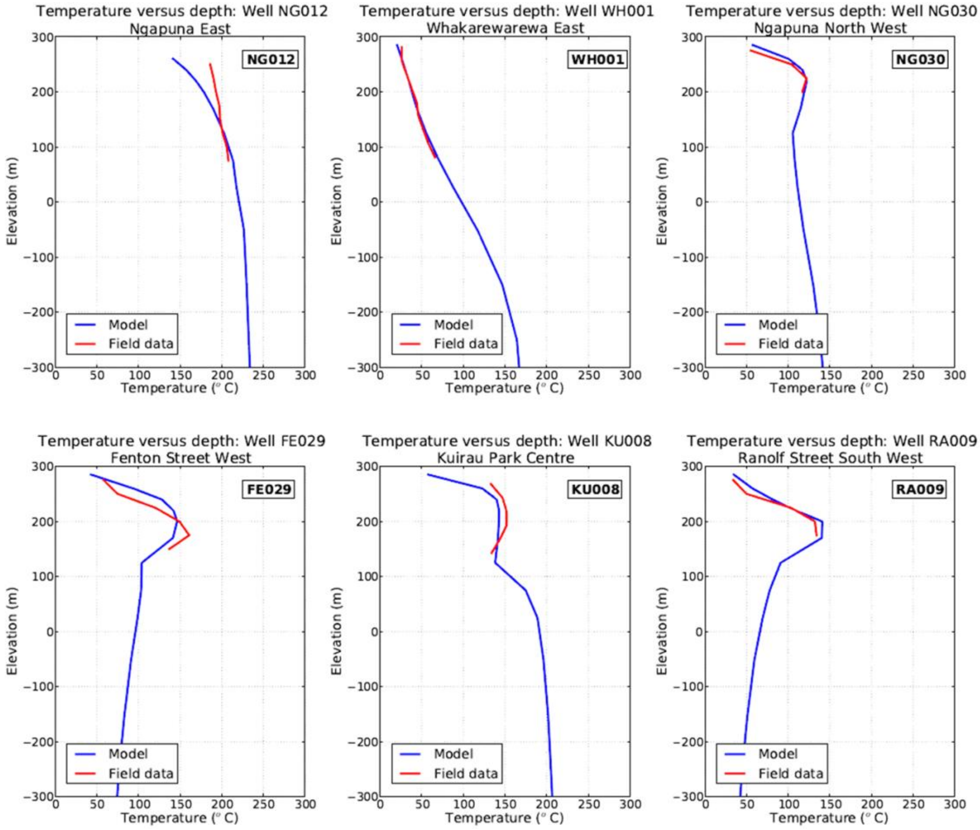
**Table 2: Deep inflows at the bottom layer of the model**

| Area | UOA Model 3 (Bottom: 2000m) | | IRL Model 2 (Bottom: 570m) | |
|---|---|---|---|---|
| | Mass t/day | Temp ($^0$C) | Mass t/day | Temp ($^0$C) |
| Kuirau Park | 6,400 | 255 | 2.420 | 200 |
| Ngapuna Stream | 15,670 | 270 | 17,300 | 220 |
| Whakarewarewa | 38,500 | 245 | 30,320 | 200 |

## 6. NATURAL STATE MODELLING (1800-1950)

The natural state represents the unchanging state of the field before the field exploitation. To simulate such a state, the model is run until a steady state is reached. There is little field data from that times period to compare the model results. However a few parameters are known or have been estimated:

- The locations of the three major geothermal areas and the magnitude of surface heat/mass flow in Whakarewarewa (Burnell and Kissling, 2005) (Figure 1, Table 3).
- Pre-exploitation pressures inferred by Grant (1985)
- Temperatures, used for natural state and production calibration (assuming no significant distribution changes):
  - Temperature contours at 180 masl from electronic records obtained from Bay of Plenty Regional Council (Candra and Zarrouk, 2013). (Figure 11)
  - Downhole temperature profiles for 155 wells from Ministry of Works reports. (




  - 
  - **Figure 12**)

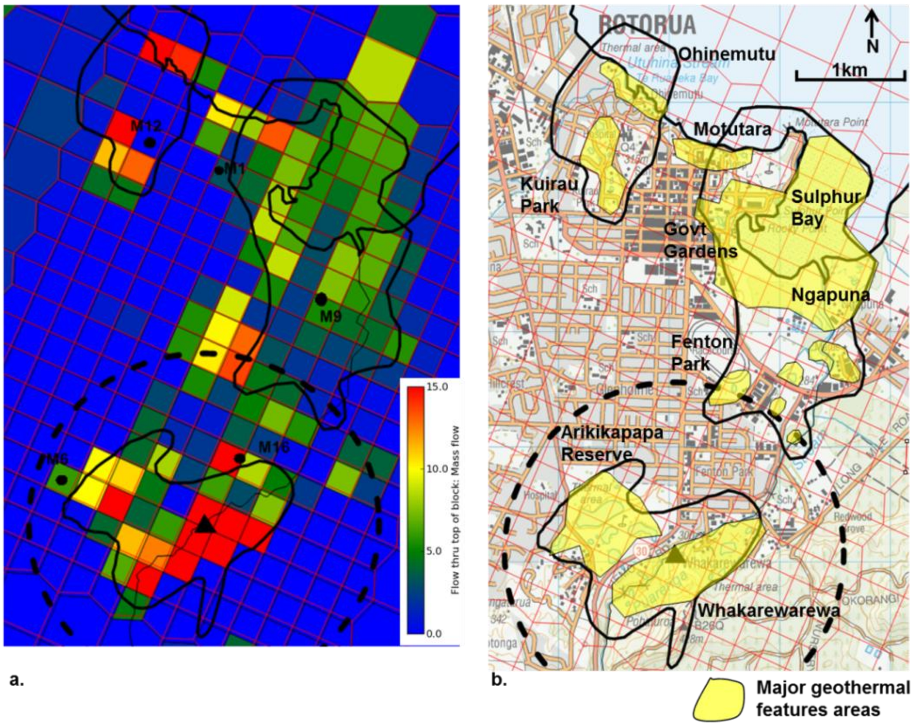



**Figure 9: Natural State conditions: a. Model Surface mass flow (kg/s) b. Rotorua city and major surface features (from topomap.co.nz)**

Areas of surface activity in the model, as shown by mass flows (Figure 9), are located within the model blocks that correspond with the known locations of surface discharging features. Areas such as Ohinemutu, Kuirau Park, Fenton Park, and Whakarewarewa are represented well in UOA Model 3.

- Heat and mass flows from Whakarewarewa are, respectively 266 MW and 29,300 tonnes/day compared with inferred values of 300 MW and 34,560 tonnes/day.
- Kuirau Park: 14.3 MW and 1,616 tonnes/day.
- Ngapuna/Puarenga Stream: 95MW and 9,670 tonnes/day.

Note that there are no corresponding quantitative estimations of the heat and mass flows in the second and third locations.

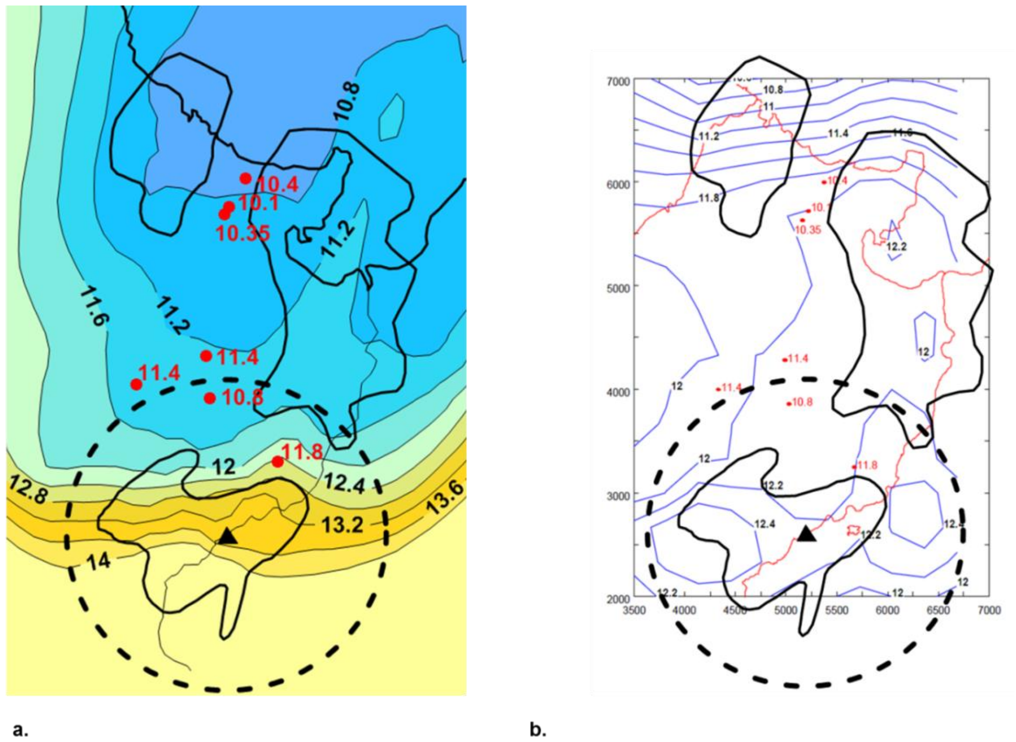



**Figure 10: Natural State: a. Model pressure (bar) contours (black) and pressure infered by Grant (1985) (red) b. IRL model (Burnell and Kissling, 2005) pressure contour (blue).**

Pressures at 180m absl are slightly higher than the inferred values particularly at Government Garden (11 > 10.4 bars) and at Whakarewarewa (12.4 > 11.8 bars) but show a similar southeast-northwest gradient. When compared to previous models (Burnell and Kissling, 2005) pressure points are closer to the measured data available (e.g. at Government Garden: 12 (IRL) > 11 (UOA3) > 10.4 bars). UOA Model 3 allows for a more accurate representation of the water table which strongly influences shallow reservoir pressures.

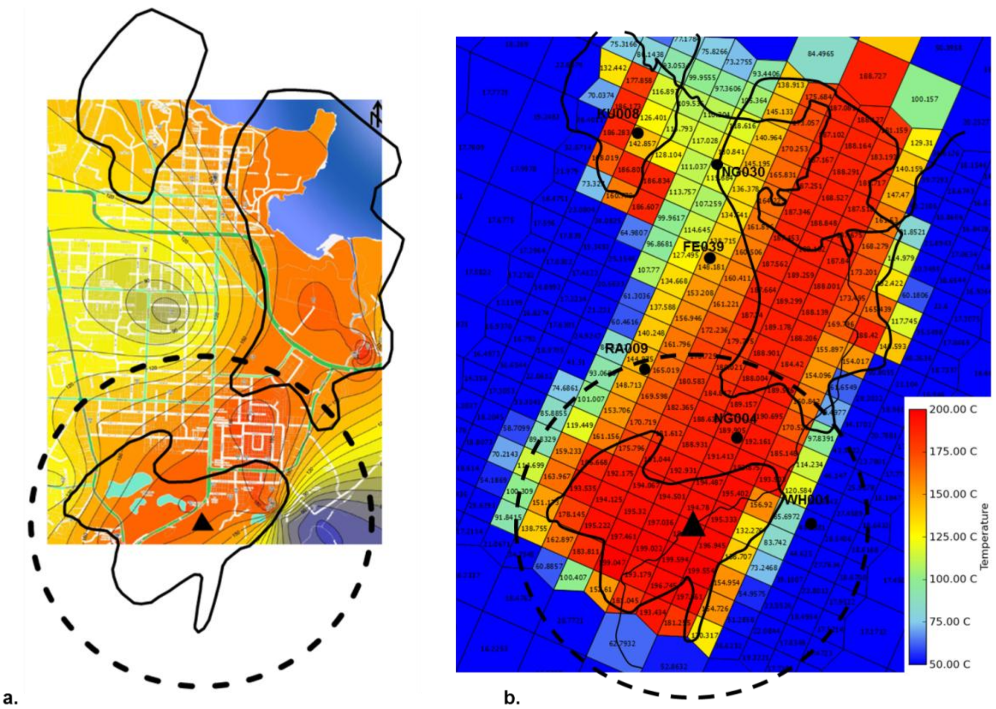



**Figure 11: Temperature distribution at 180mRL: a. Candra and Zarrouk (2013). b. UoA Model 3 Temperature distribution**

Model temperatures exhibit a similar distribution to the measured temperatures reaching 190°C at Whakarewarewa and in the eastern part of Ngapuna: hot upflow in the northeast (Whakarewarewa), along the Ngapuna Fault and at Kuirau Park. Temperatures also indicate a north-northeast geothermal outflow across the Buried Dome and a shallow cold water inflow from the West between Arikikapakapa and Kuirau Park.

The apparent mismatch in Fig 11 at Kuirau Park between the model estimates and measured data (Candra, 2013) is due to the lack of field data used to define the temperature contours in this area. Similarly the increasing temperatures at western edge of the measured data contours are an artifact of the contouring process. The model estimates of colder water outside of the upflow are consistent with the resistivity information previous temperature distribution map (Wood, 1985).

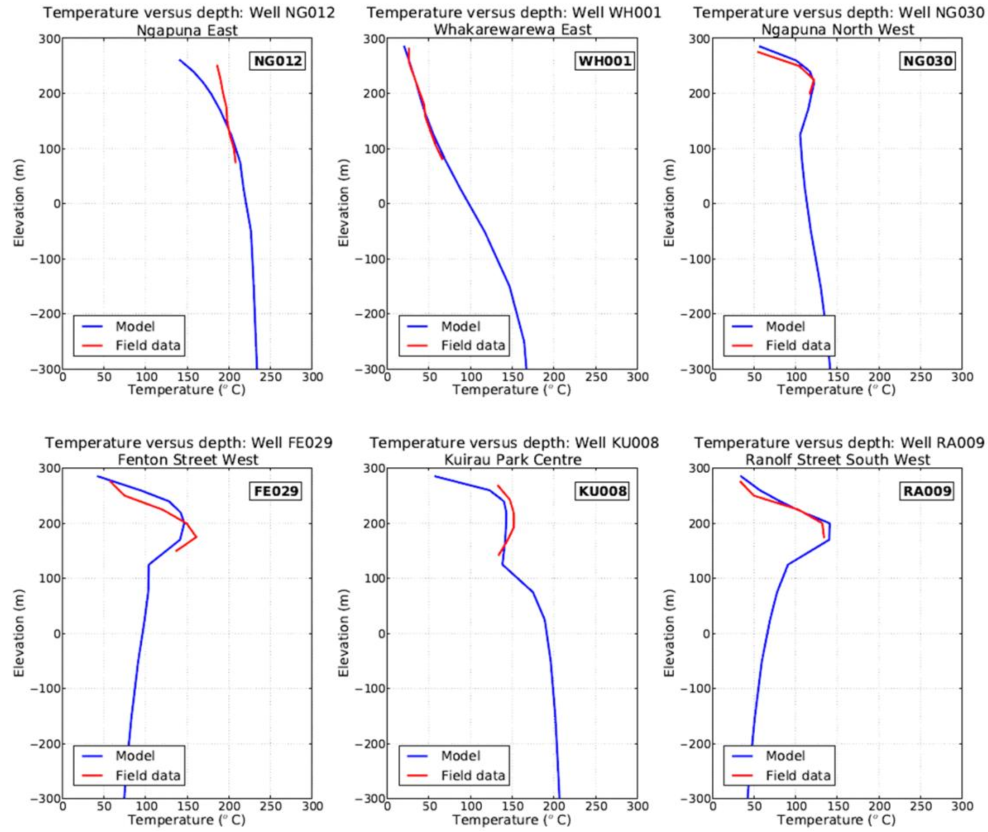



**Figure 12: Down-hole temperature for a few wells across the RGF: red for field data, blue for model results.**

Six down-hole temperatures plots are shown in

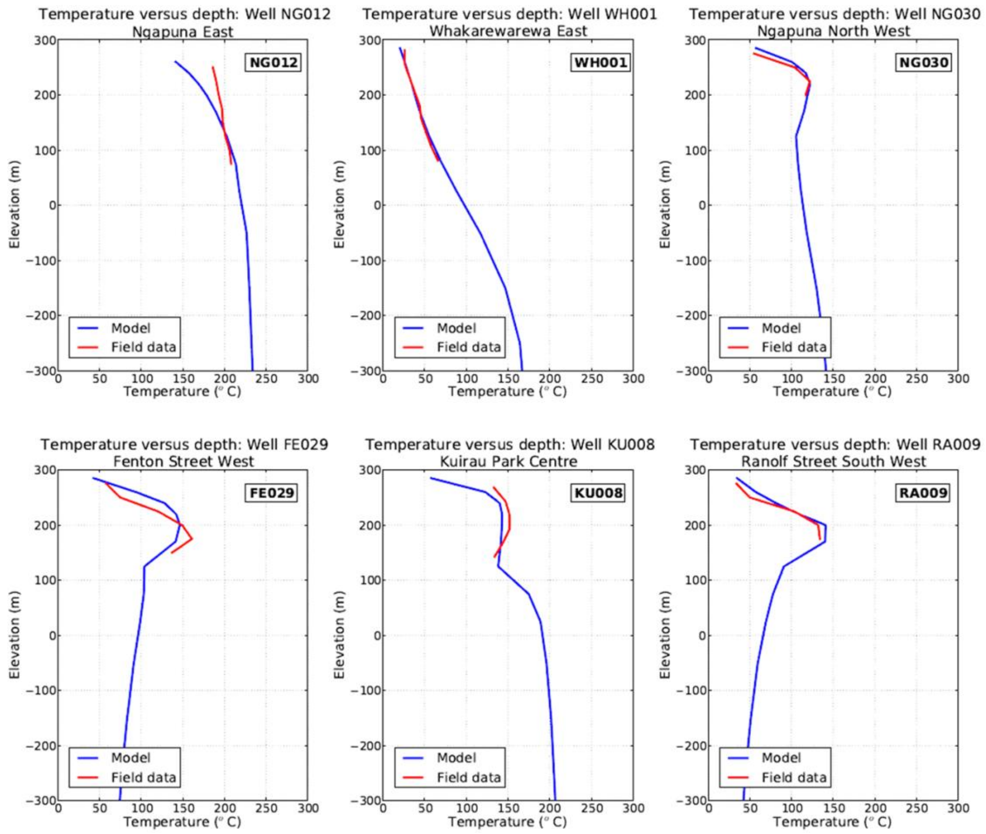


**Figure 12**. Their location is indicated in Figure 11c. Similar plots were made for 130 different wells and most show a similar level of agreement between model results and data.

These exhibits some of the typical profiles which account for wells located:

- Within the main part of the upflow (NG012),
- Close to the upflow zone but cooled down by side water flow (WH001),
- Within the lateral flow of the geothermal fluid (showed by the temperature inversion) across the rhyolite dome (NG030, FE029, KU008, RA009) (Figure 13)

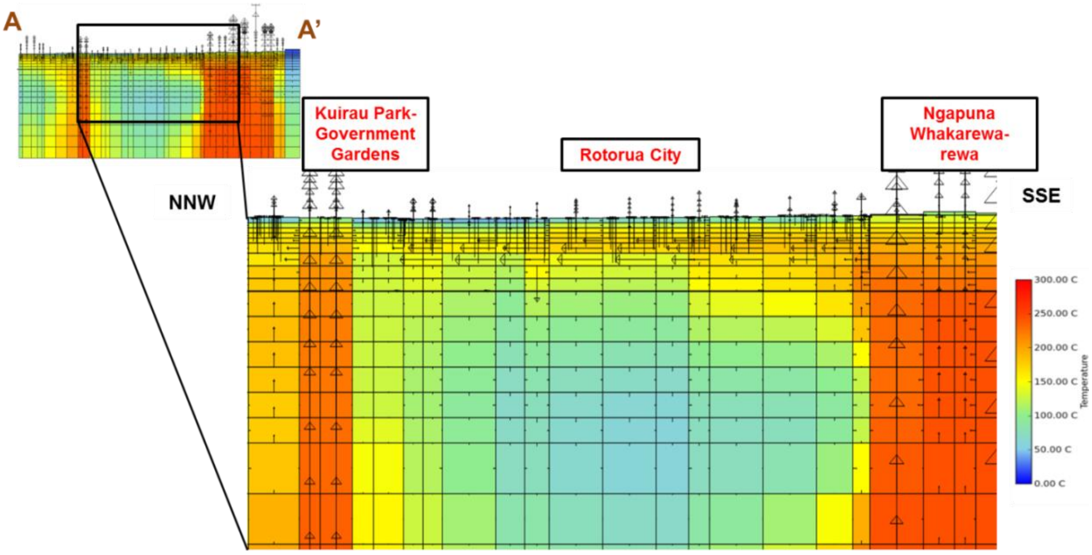



**Figure 13: UOA Model 3: NW-SE cross section of the temperature distribution (location highlighted in Figure 4)**

## 7. PRODUCTION MODELLING (1950-1986)

### 7.1. Pre Wellbore Closure

The model was run for 36 years using the withdrawal pattern shown in Figure 14. Little information on the production distribution is available; production and injection were therefore applied uniformly across the known production and injection wells.

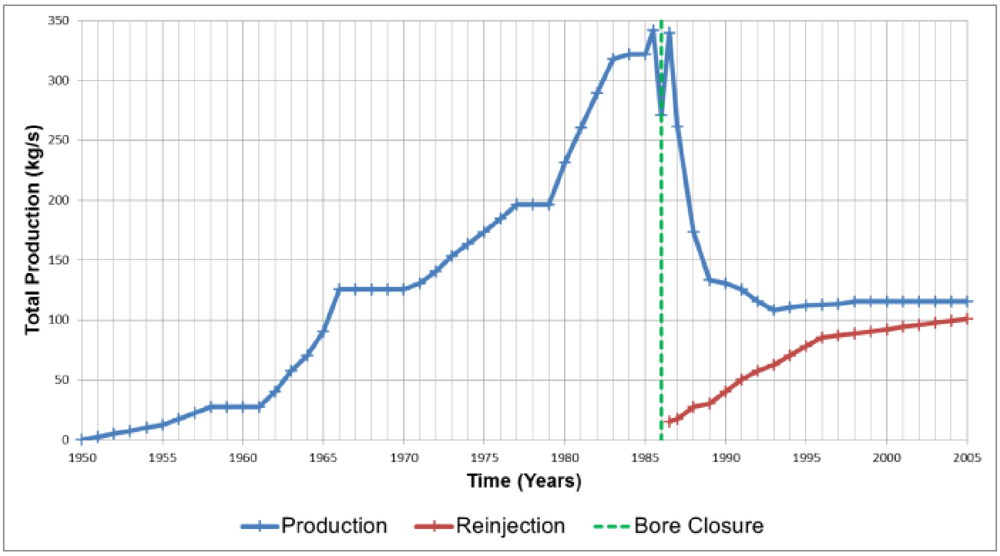



**Figure 14: Rotorua Field Production History (from Gordon et al., 2005)**

There is also relatively little measured data available regarding the impact of the exploitation of the system however the model matches the qualitative observations well. For example in 1986, the heat flow measured from Whakarewarewa had dropped to an estimated 158 MW and the model predicts a similar decline. The model also predicts a significant decline in the flow at Kuirau Park agreeing with observations that the Kuirau Park Lake essentially ceased overflowing during this period (Burnell and Kissling, 2005). The modeled production-induced pressure drop within the RGF is slightly higher than the observed value of 0.2 bar with declines of 0.2-0.25 bar (Figure 15). Finally the modeled downhole temperatures are also a good match with the measured data during the exploitation period.

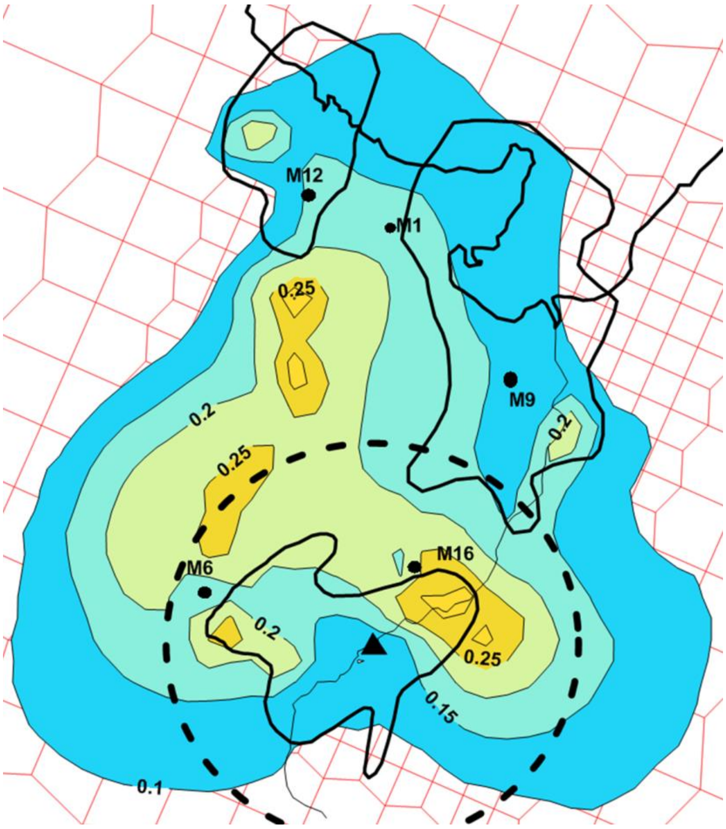



**Figure 15: Pressure drawdown between 1950 and 1986 (bar).**

### 7.2. Post Wellbore Closure (1986-2005)

To model the impact of the 1986 Bore Closure Programme all wells within the exclusion zone were shut; injection wells were added and the model was run for another 19 years using the estimated data presented in Figure 14. The model was then calibrated using measured transient pressure data recorded in 5 monitor wells (M12, M1, M9, M16 and M6). The measured data and model predictions are shown in Figure 16. In all cases the match is quite good though in most cases the model tends to predict a more rapid recovery than the wellbore measurements especially in the vicinity of Whakarewarewa.

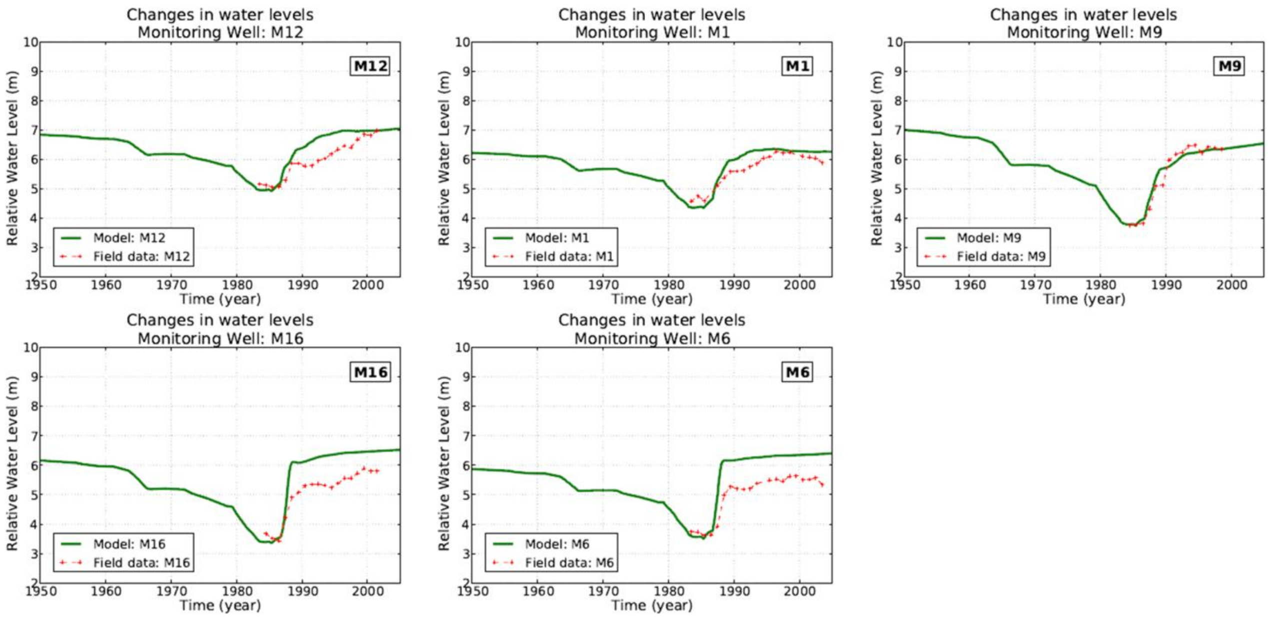



**Figure 16: Water levels response to production history for monitoring wells**

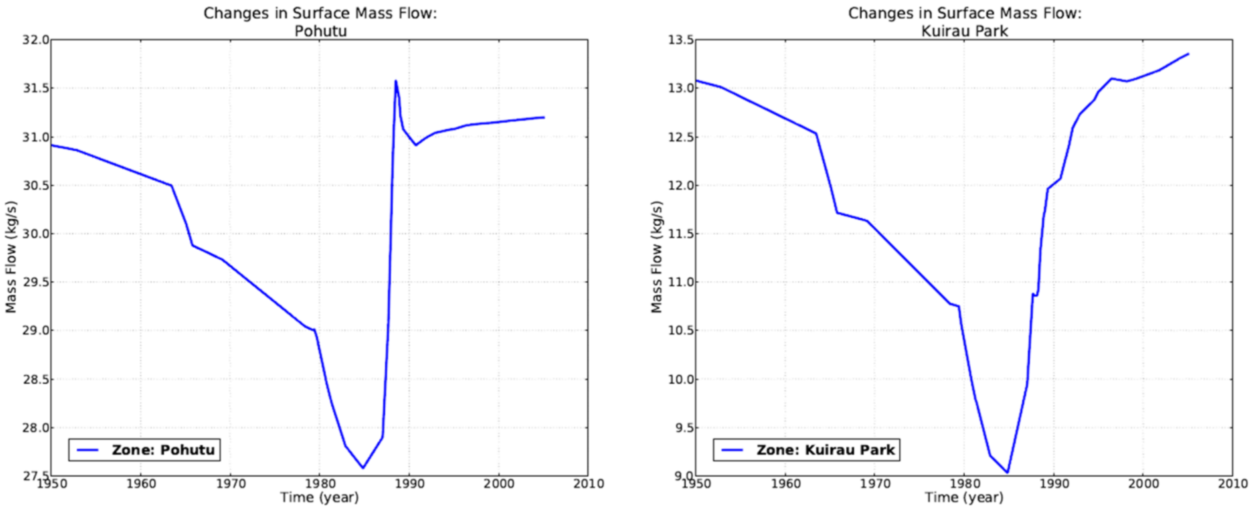



**Figure 17 : Surface mass flow evolution at Whakarewarewa and Kuirau Park**

By 1988 the model predictions for mass and heat flows have recovered levels close to the natural state. This is consistent with the observations the recovery of geysers which began erupting again in the late 1980's - early 1990's for the first time since the 1970's. Also the springs in Kuirau Park and Government Gardens began overflowing again during this period as they had prior to the exploitation of the field.

By 2005, the mode predicts that the heat and mass at Whakarewarewa have recovered to their pre-exploitation state. Thus it overestimates the recovery of the system as field observations show that some of the surface features have yet to regain activity. For example Papakura geyser did not show signs of activity again until October 2013.

Table 3 summarizes comparisons of the model predictions and measured data for heat and mass flow at various locations recorded at different times. In most cases the agreement is quite good including along the Puarenga Stream area where the model predicts a heat flow of 85 MW in 1990 which is a close match to the previously estimated figure of 77±20 MW (Glover, 1992).

As discussed in the previous section the model does not correctly predict the cessation of mass flow from Kuirau Park by 1986 but it does a good job of matching the recovered flow rate of about 1,728 tons/day (Burnell and Kissling, 2005) measured in 1993.

**Table 3: Surface features heat and mass flow**

| Surface features | Date | Measured | UOA Model 3 |
|---|---|---|---|
| Whakarewarewa Heat Flow (MW) | 1950 | 300 | 266 |
| | 1967 | 228 | 251 |
| | 1985 | 158 | 228 |
| | 2000 | >216 | 265 |
| Whakarewarewa Mass Flow (t/d) | 1950 | 34.560 | 29,300 |
| Ngapuna Heat Flow (MW) | 1990 | 77 | 85 |
| Kuirau Park Mass Flow (t/day) | 1986 | 0 | 1,200 |
| | 1993 | 1,728 | 1,573 |

## 8. NEXT STEPS

Temperatures and pressure drawdown are satisfactory when compared with the field data available; however surface mass and heat flow of geothermal features still need further calibration.

Horizontal and vertical refinement has been effective for the overall representation of the lateral flow of geothermal fluid however it could not account for some of the finer mechanisms. Particularly some wells located within the same model block that show very different behavior: upflow, lateral flow or cold lateral flow. It is especially true for blocks at the edge of the geothermal reservoir and close to surface features where more accurate predictions will require finer horizontal refinement of the grid. Further vertical refinement of the grid would allow more accurate representation of the water table and better calibration to actual water levels. This will in turn allow a better match to shallow pressures within the reservoir and more accurate transient response to the system's exploitation, including the cessation of flow from Kuirau Park. It would also help in matching abrupt temperature inversions seen in some wells.

Moreover given the high number of calibration variables (temperature, pressure, surface mass and heat flow), forward modeling is a challenging and time consuming task. Complementing forward modeling processes, inverse modeling could be used to achieve some level of automatic calibration. This requires a framework to identify variables, quantify the confidence of each ones and hierarchized the importance of the parameters to be fitted.

Given the large chemical data array of springs and wellbores collected throughout various campaigns, modeling of the RGF which includes chloride concentration (EOS1) may be relevant (Pruess, 1991).

## 9. CONCLUSIONS

A new model of the Rotorua geothermal field has been developed that represents the shallow unsaturated zone and explicitly includes important structures identified in the conceptual model. The model gives a good overall match to the natural state of the field and to the response to the 1986 bore closure programme. Manual methods have been used to calibrate the model against surface activity, temperatures at 180mRL and downhole temperatures from ~130 shallow wells and downhole pressure.

More work is however needed to obtain a better match of the pressure drawdown at Kuirau Park and Whakarewarewa as well as the surface features variation in heat and mass flow. Particularly the relation linking pressure drawdown and surface discharge is to be further explored. This can be done by further forward calibration work, inverse modeling (using PEST or iTOUGH2) and by increasing the resolution of the grid.

The model will prove to be a useful tool for studying and understanding the behaviour of the surface features that are an extremely important to Rotorua and New Zealand in general.

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