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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 small city and has an 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 resulted in a decline of the surface features. In 1986, a bore closure program was introduced and geyser activity and hot springs have rejuvenated progressively with some springs overflowing recently for the first time in over 30 years.

Two three-dimensional numerical models of the Rotorua system have been developed to study the response of surface features to production and reinjection, called here UOA Model 3 and 4. UOA Model 3 and 4 differ from previous models by having a much finer layer structure in the shallow zone − minimum block size of 250m^2 x 10m and 125m^2 x 5m respectively − and by including an unsaturated zone. This enables a better representation of near-surface mass and heat flows. They also include the complex structural and lithological structures associated with the asymmetrical caldera collapse setting of the Rotorua geothermal system. Both models have been calibrated against a large number of shallow temperatures, water table levels, the locations and magnitudes of surface activity and 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 city and contains one of New Zealand's last remaining areas of major geyser activity at Whakarewarewa (Figure 1). The geothermal resource and features have 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).

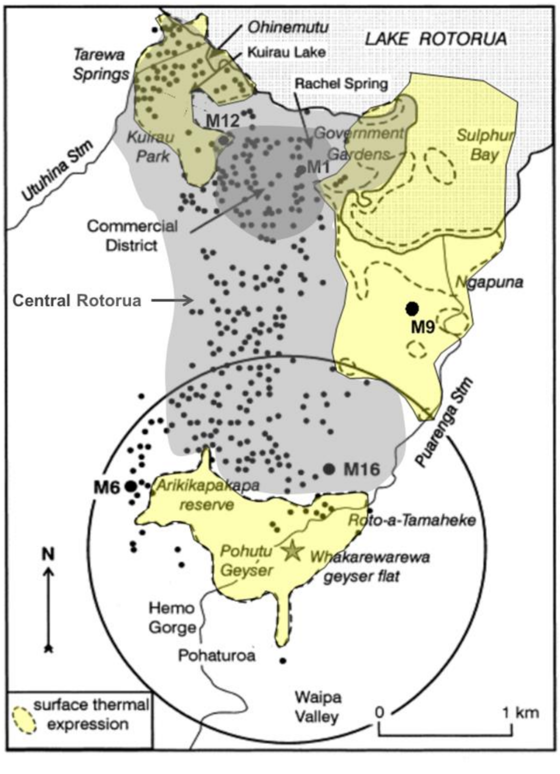


Figure 1: Surface features and distribution of geothermal and monitoring wells in Rotorua city in 1985 (From Scott and Cody 2000)

Exploitation of the geothermal heat began with traditional use which was followed by a phase of intensive geothermal fluid abstraction from shallow bores. 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 owned wells in Rotorua City and a royalty scheme was introduced 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 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, the unsaturated zone 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, which induces large convective cells of hot rising fluid forming 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).

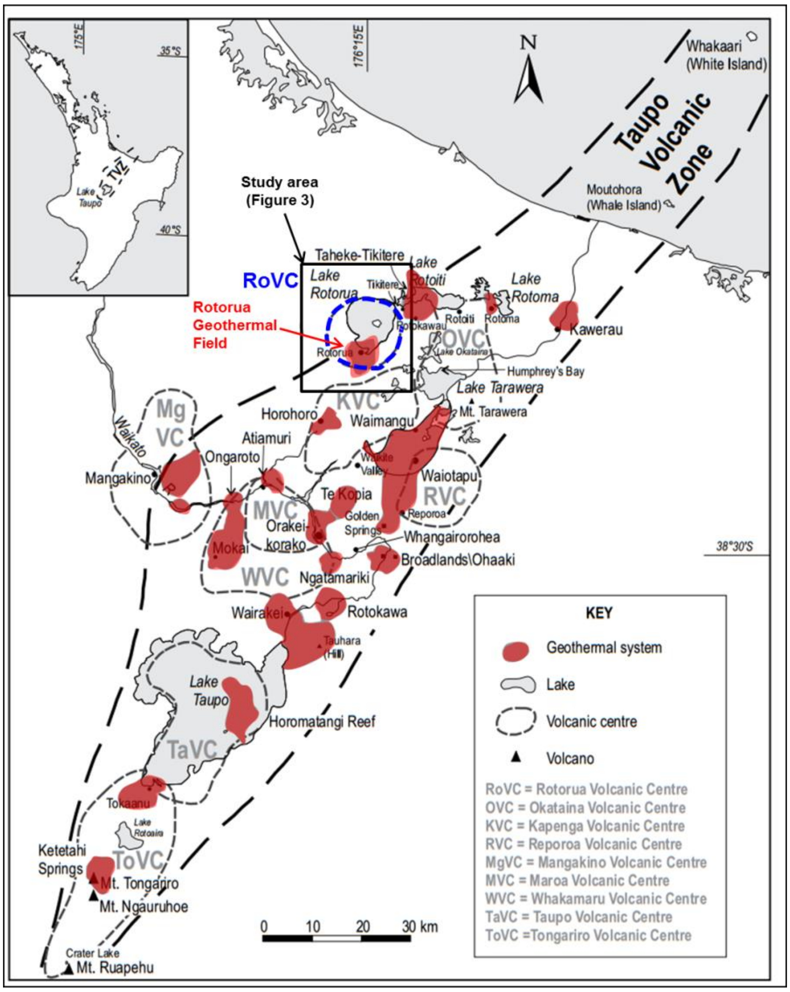


Figure 2: Location of the RGF (in red) within the Rotorua Caldera (in blue) (From Cody, 2007)

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 geological timeline of the formation of relevant structures within the RGF can be summarized as follows (Ashwell et al., 2013):

- 240-200ka: Single cataclysmic eruption of the Rotorua volcanic centre which resulted in the deposition of an extensive ignimbrite sheet, the Mamaku Ignimbrite (mauve in Figure 3). The extrusion led to an asymmetrical multiple-block caldera collapse syn-eruption.

- 200ka: Dike-fed lava domes eruptions (Utuhina Group) controlled by existing faults (purple in Figure 3).

- 200-60ka: 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).

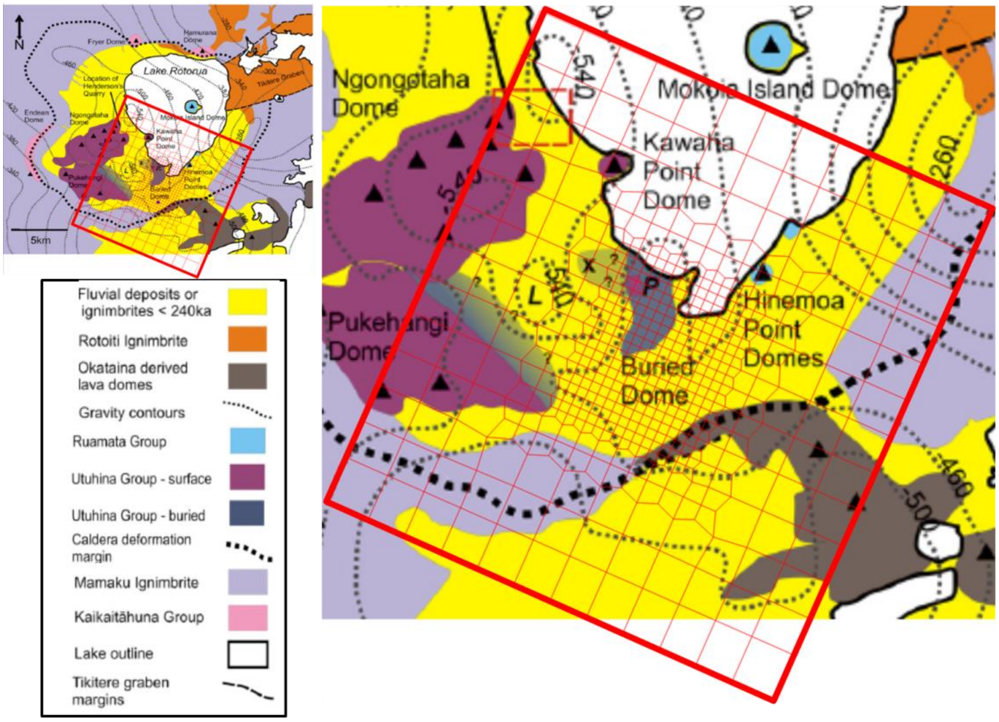


Figure 3: Geological map of the Rotorua Caldera, gravity anomaly contours (µN/kg) (Ashwell et al., 2013). UOA Model 3 grid shown in red.

Studies of the morphology of the caldera (centered on a gravity anomaly to the northwest of the city) (Figure 4) 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. This matter will be discussed in the following section.

3. CONCEPTUAL MODEL

Prior to the well closure, an important amount of data regarding wells and springs (e.g. lithology, temperature, pressure, feedzone/flow rate, fluid composition) of the Rotorua field was collected as part of the Rotorua Geothermal Monitoring Programme. There are a large number of wells (several hundred) but most are less than 300m deep. There is, therefore, limited data for the deeper part of the field. Nonetheless from the following observations, a conceptual model accounting for the key features 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). Shows good fracture permeability (Wood, 1992).
- 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 the Rotorua caldera collapse (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.

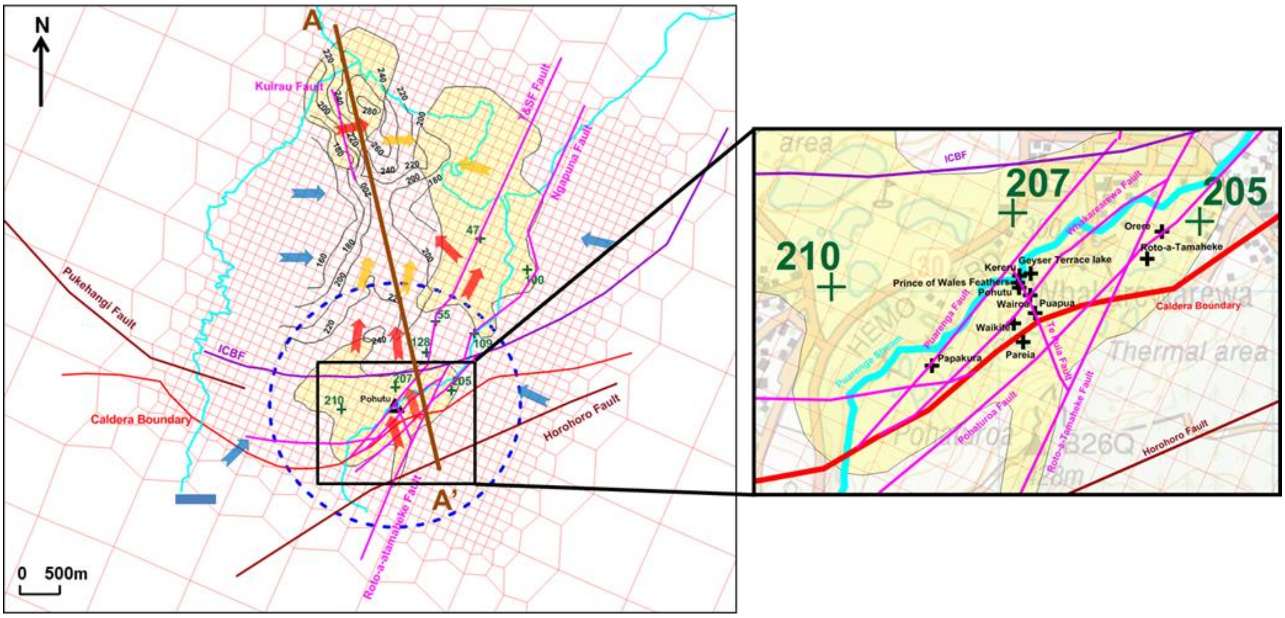


Figure 4: Geological and structural setting of the RGF and detailed map of Whakarewarewa (arrows show the lateral fluid flow within the shallow parts of the RGF).

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).

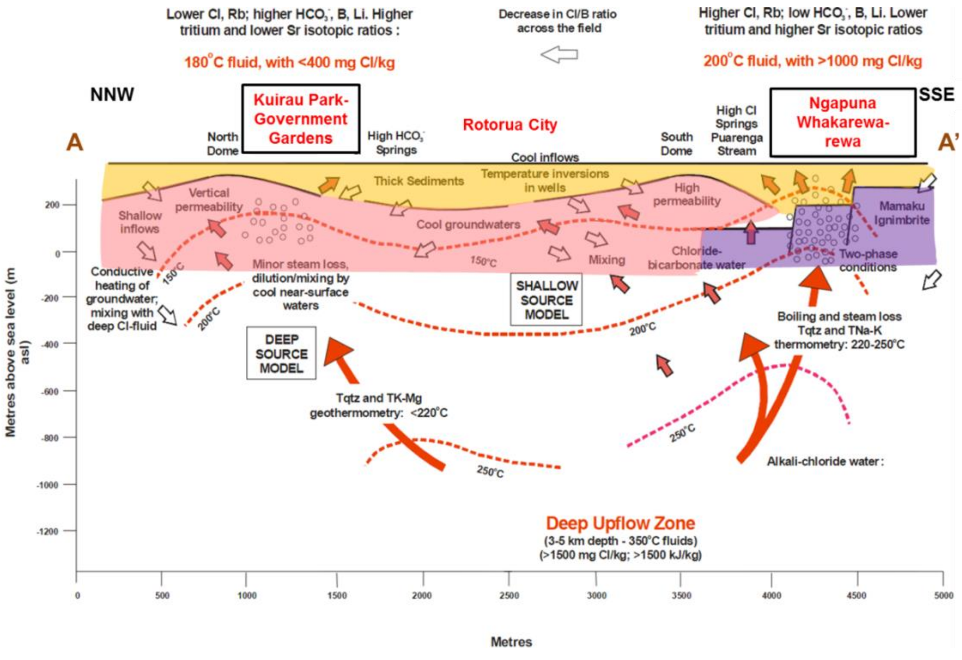


Figure 5: Cross section of the RGF conceptual model (location highlighted in Figure 4) (From Gordon *et al*., 2005)

4. COMPUTER MODELLING

Computer modeling together with a 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. The conclusions from this modelling study 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), called here IRL Model 2.

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.

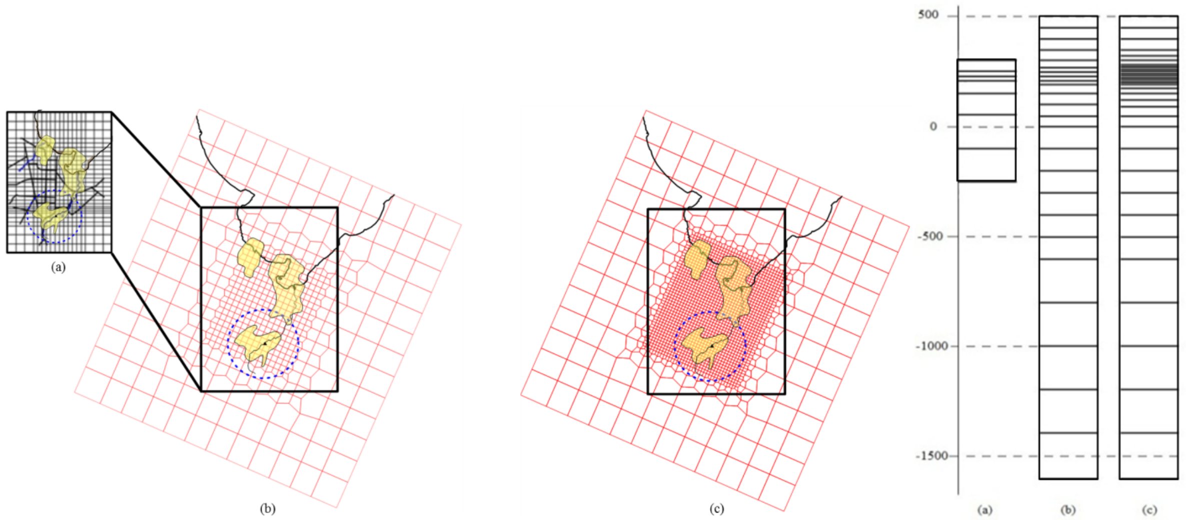


Figure 6: Grid layout and layer structure for (a) IRL Model 2, (b) UOA Model 3 and (c) UOA Model 4.

The complex caldera collapse structures are also included in the model: explicit faults, down-faulting of the Mamaku Ignimbrite, the Rhyolite dome as shown in Figure 4 (see Figure 7).

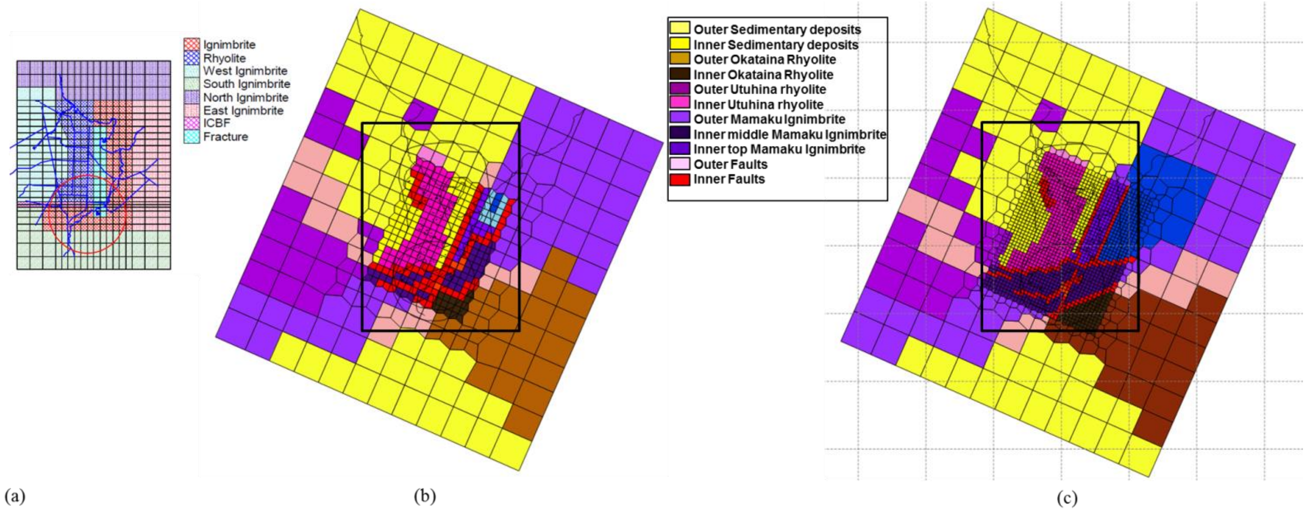


Figure 7: Geological settings at 100 masl: IRL 2005 (a), UOA Model 3 (b) and UOA Model 4 (c).

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

Table 1: Summary of models of Rotorua Geothermal Field

Category	IRL Model 2	UOA Model 3	UOA Model 4
Grid area	6 km x 8.5 km	12.4 km x 18.3 km	12.4 km x 18.3 km
Grid depth	570 m	2,000 m	2,000 m
Blocks	3,550	11,302	48,034
Layers	7	23	30
Minimum block size	125*250 m^2	250*250 m^2	125*125 m^2
Minimum block height	20 m	20 m	5 m
Orientation (angle to N-S)	0^0	23.7^0	23.7^0
Rainfall rate	1.3 m/year	1 m/year	1 m/year
Infiltration rate	7.5%	10%	10% - 8%
Surface	Planar water table, 40m lower at the lake	Follows topography & lake bathymetry	Follows topography & lake bathymetry
Equation of State (EOS)	1 (pure water + chloride tracer)	4 (air + water)	4 (air + water)

The main objective of our modelling study is to provide a more detailed representation of the behavior of the discharge features at Rotorua. This led to the implementation of a finer layer structure in UOA Model 3, 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).

UOA Model 4 was further refined from UOA Model 3 to allow higher resolution in modelling the details of actual water levels and topography which strongly controls the behavior of individual surface features.

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 masl 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. Over the urbanized zone an infiltration rate of 8% is implemented in UOA Model 4 to account for paved areas and the existing drainage system.

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).

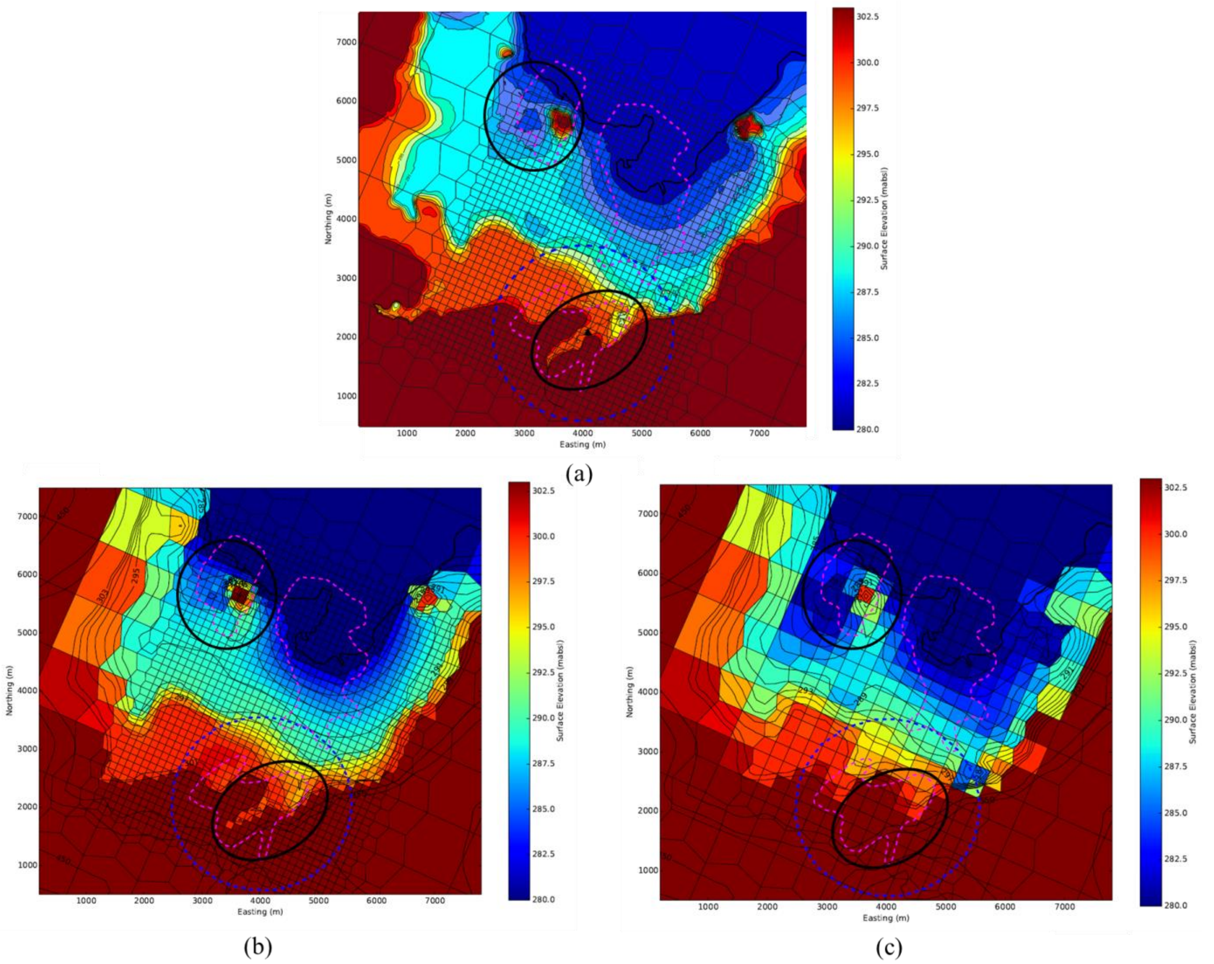


Figure 8: Surface elevation of the RGF. (a) Field data, (b) UOA Model 4 and (c) UOA Model 3.

The refined model offers a more detailed representation of surface elevations and includes small-scale structures especially in the vicinity of Kuirau Park and Whakarewarewa, areas of particular interest.

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, UOA Model 4 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	IRL Model 2 (Bottom: 570m)		UOA Model 4 (Bottom: 2000m)		UOA Model 3 (Bottom: 2000m)	
	Mass t/day	Temp (^{0}C)	Mass t/day	Temp (^{0}C)	Mass t/day	Temp (^{0}C)
Kuirau Park	2.420	200	6,750	255	6,400	255
Ngapuna Stream	17,300	220	18,790	270	15,670	270
Whakarewarewa	30,320	200	34,560	245	38,500	245

6. NATURAL STATE MODELLING (1800-1950)

The natural state represents the unchanging state of the field before 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 with which to compare the model results. However a few parameters are known or have been estimated:

- Locations of the three major geothermal areas and magnitude of surface heat/mass flow in Whakarewarewa (Burnell and Kissling, 2005) (Figure 9, Table 1).
- Pre-exploitation pressures inferred by Grant (1985) (Figure 10) and post-recovery water levels (Gordon *et al*. 2005)
- Temperature contours at 180masl 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)

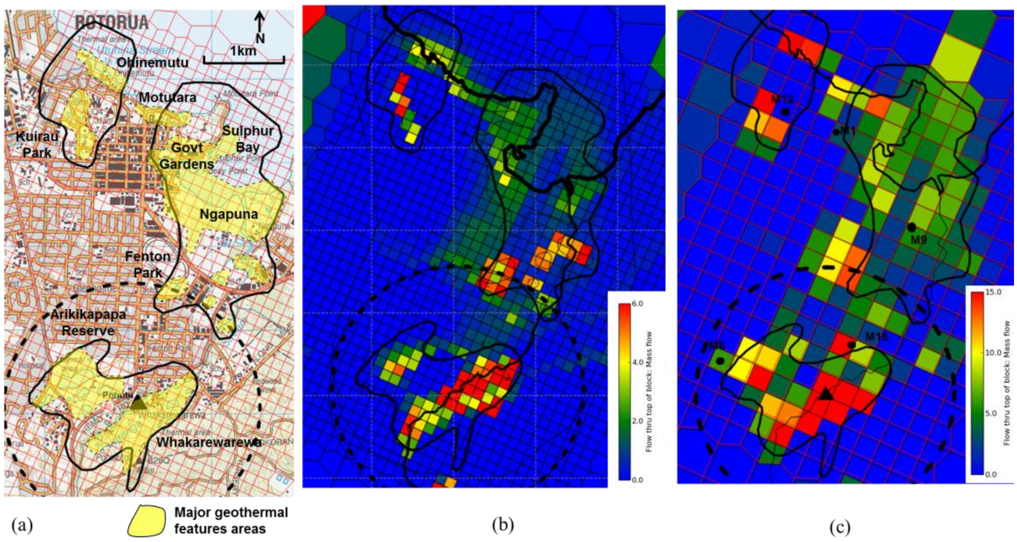


Figure 9: Natural State conditions for surface mass flow (kg/s): (a) Rotorua city and major surface features (from topomap.co.nz), (b) UOA Model 4, (c) UOA Model 4

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, Arikikapapa Reserve and Whakarewarewa are represented well in UOA Model 3 and 4. Kuirau Park and surface occurrences across the Ngapuna/Pueranga stream sector are described much more accurately in UOA Model 4.

- Heat and mass flows from Whakarewarewa are respectively 266 MW and 33,540 tonnes/day (UOA Model 3) and 245 MW and 30,000 tonnes/day (UOA Model 4) compared with inferred values of 300 MW and 34,560 tonnes/day.
- Kuirau Park: 14.3 MW and 1,616 tonnes/day (UOA Model 3); 14.7 MW and 1,598 tonnes/day (UOA Model 4).
- Ngapuna/Puarenga Stream: 86MW and 10,100 tonnes/day (UOA Model 3 and 4).

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

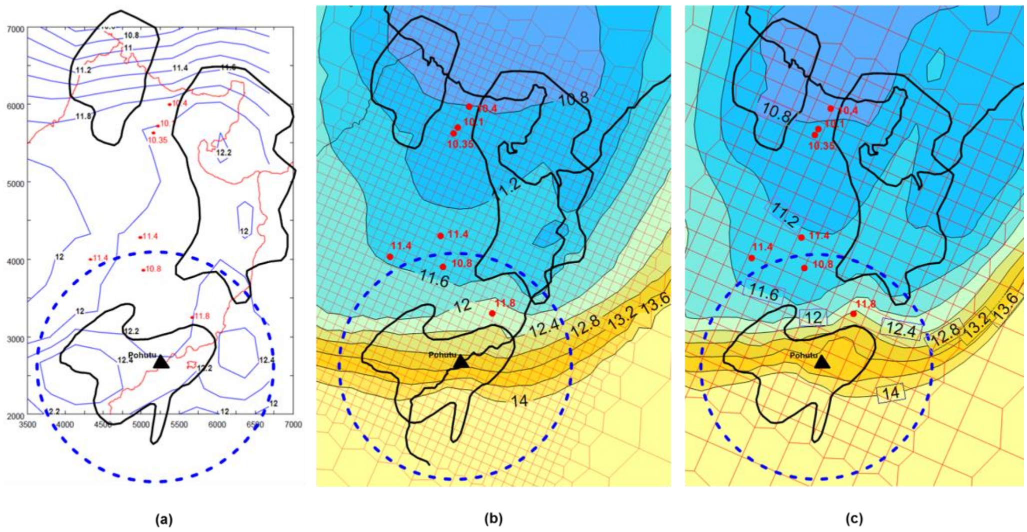


Figure 10: Natural state pressures and pressure inferred by Grant (1985) (bar): (a) IRL Model 2 (Burnell and Kissling, 2005) (b) UOA Model 4 and (c) UOA Model 3.

Pressures at 180m absl are slightly higher than the inferred values particularly at Government Garden and Whakarewarewa but show a similar southeast-northwest gradient (Figure 10). When compared to previous models (Burnell and Kissling, 2005) pressures are closer to the measured data available (Table 3).

Table 3: Comparison of inferred and simulated natural state reservoir pressure

Reservoir Pressure (bar) at 180 masl	Inferred by Grant (1985)	IRL Model 2	UOA Model 3	UOA Model 4
Government Garden	10.4	12	11	10.8
Whakarewarewa	11.8	12.2	12.4	12.1

The temperatures for UOA Model 3 and 4 exhibit a similar distribution to the measured temperatures reaching 190°C at Whakarewarewa and in the eastern part of Ngapuna, with a hot upflow in the northeast (Whakarewarewa), along the Ngapuna Fault and at Kuirau Park (Figure 11). Temperatures also indicate northwest ans west geothermal outflows across the Buried Dome and a shallow cold water inflow from the West between Arikikapakapa and Kuirau Park.

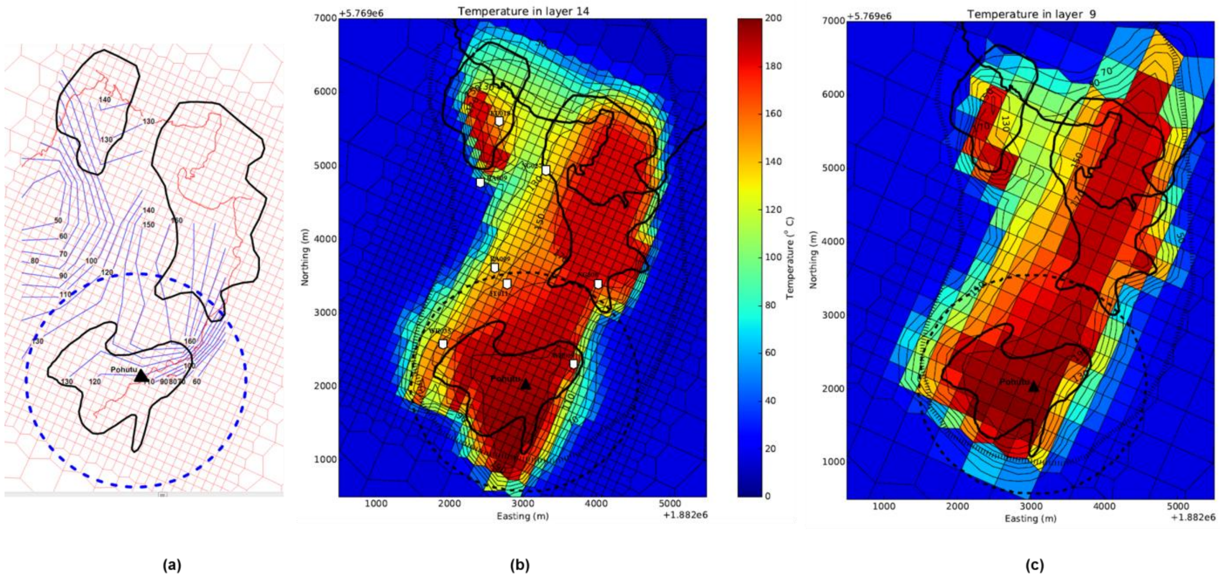


Figure 11: Temperature contours at 180masl. (a) UOA Model 3, (b) UOA Model 3, (c) Inferred by Wood (1992).

Eight down-hole temperatures plots are shown in Figure 12. Locations are indicated in Figure 11 (b). Similar plots were made for 130 different wells and most show a similar level of agreement between model results and data.

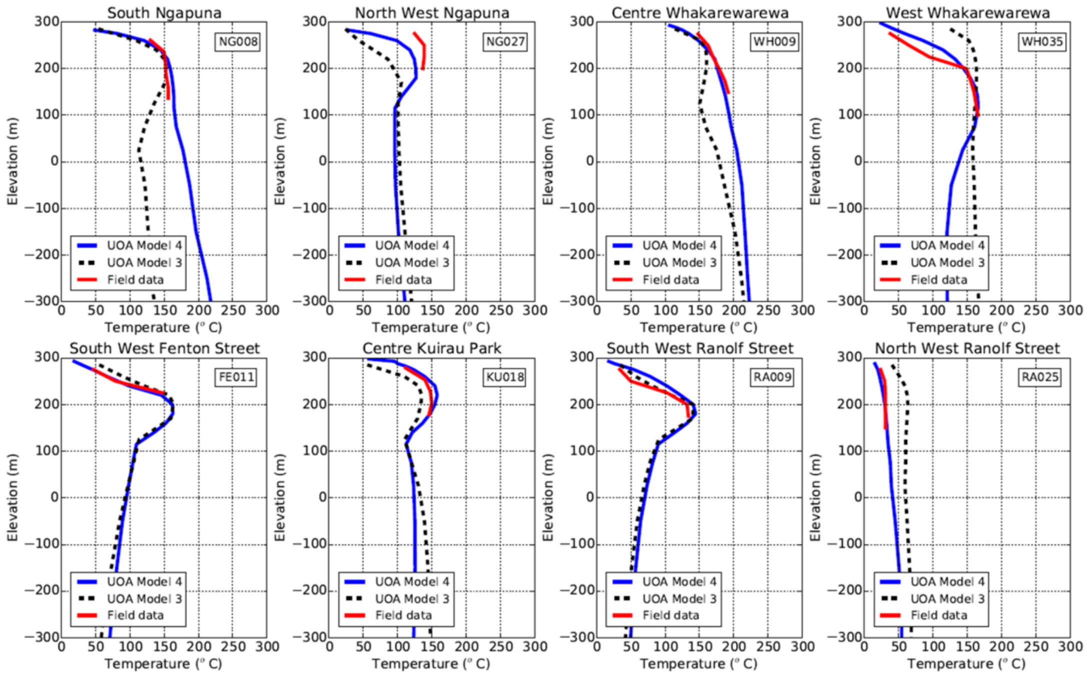


Figure 12: Well down-hole temperature across the RGF: red for field data, black (dotted) for UOA Model 3 and blue for UOA Model 4.

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

- Within the main part of the upflow (NG008 and WH009),
- Cold downflow (WH035)
- Within the lateral flow of the geothermal fluid (showed by the temperature inversion) across the rhyolite dome (NG027, FE011, KU018, RA009) (Figure 13)

The coarser model, UOA Model 3, was able to match the measured temperatures in a satisfactory manner however its block size limited its resolution for matching fine-scale mass flow behavior and thus local variations in temperature observed in the RGF. UOA Model 4 offers a better temperature match overall.

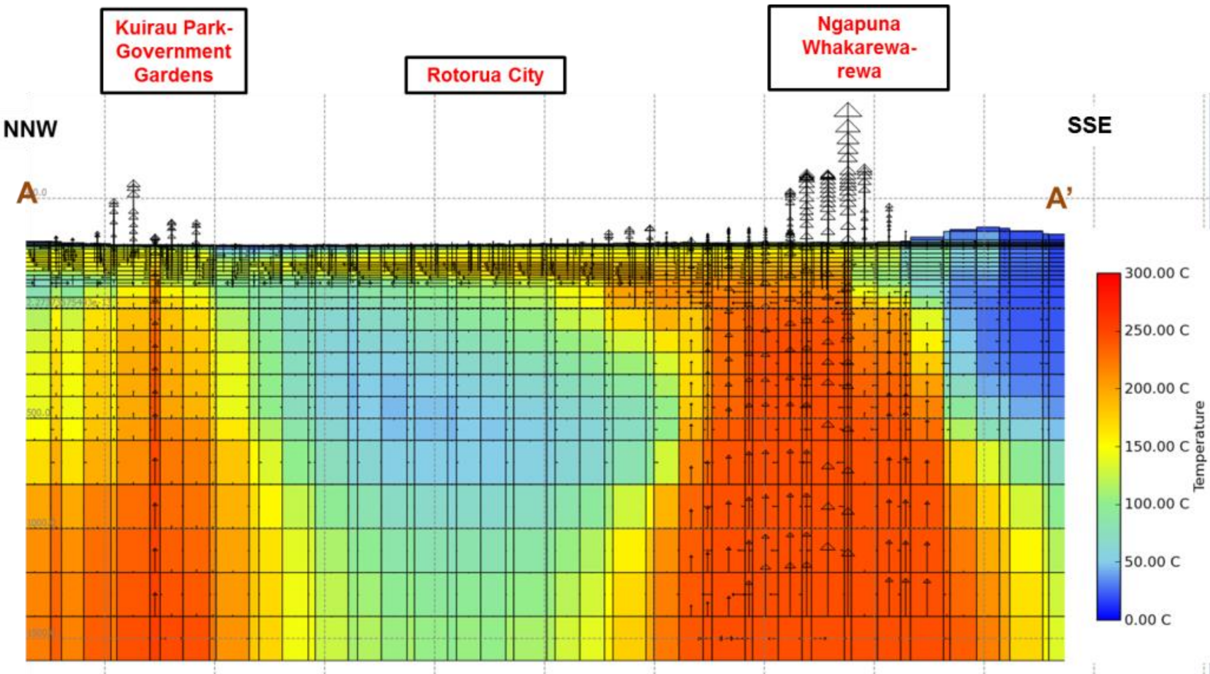


Figure 13: UOA Model 4: NW-SE cross section of the temperature distribution (location highlighted in Figure 4)

7. PRODUCTION MODELLING (1950-1986)

7.1. Pre Wellbore Closure

The models were 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. Similarly little quantitative data describing the impact of the reservoir depletion is available as the Monitoring Programme began in only the 1980's when the reservoir pressure had already significantly declined.

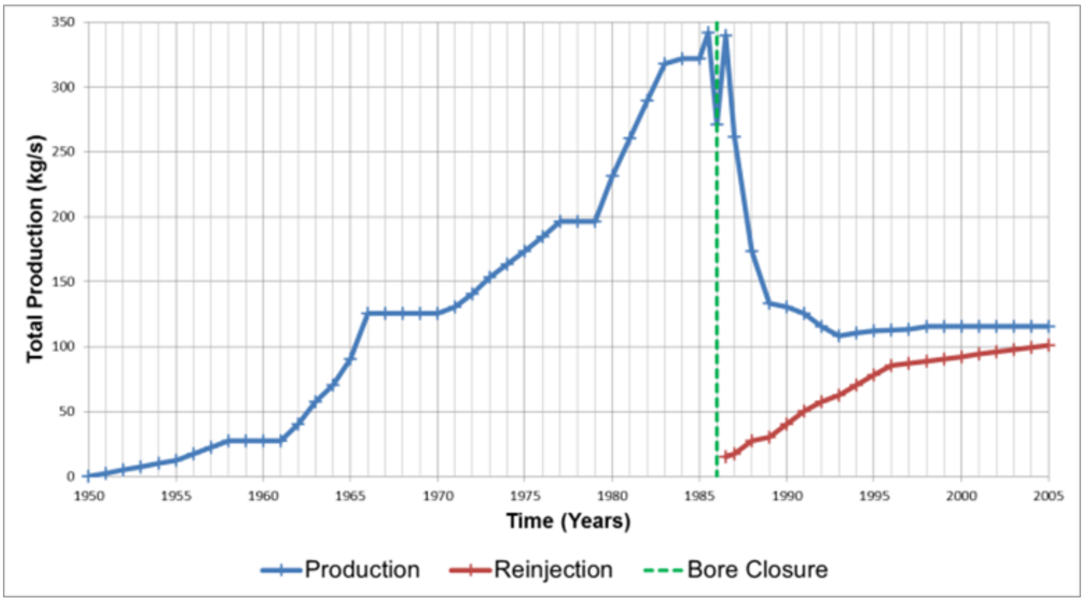
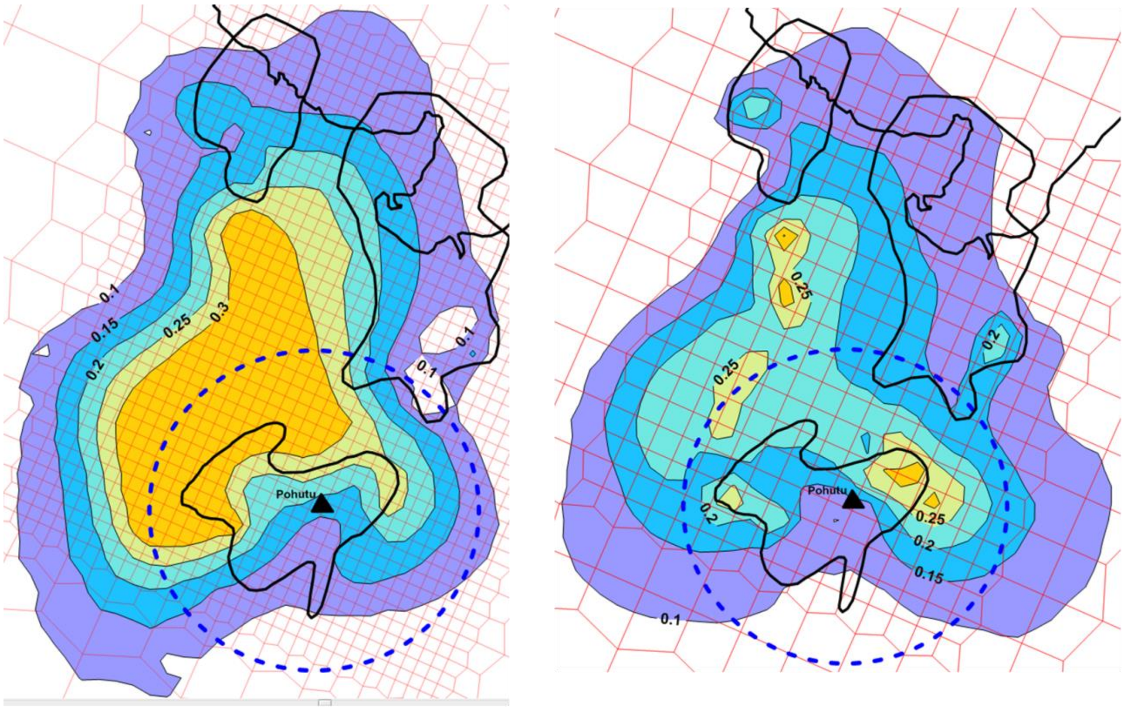


Figure 14: Rotorua Field Production History (from Gordon *et al.*, 2005)

The models match qualitative observations made during this period. For example in 1986, the heat flow measured from Whakarewarewa had dropped to an estimated 158 MW and UOA Model 3 and 4 predicts a similar decline.
The models also predict 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).



(a) (b)

Figure 15: Pressure drawdown between 1950 and 1986 (bar). (a) UOA Model 4, (b) UOA Model 3.

The modeled production-induced pressure drop within the RGF is slightly higher than the observed value of 0.2 bars with declines of 0.25 and 0.30 bar for UOA Model 3 respectively UOA Model 4 (Figure 15). Modeled downhole temperatures are also a good match with the measured data during the exploitation period.

7.2. Post Wellbore Closure

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 production and injection estimates presented in Figure 14. The model was then calibrated using measured transient pressure data recorded in 6 monitor wells (M12, M1, M9, M24, M16 and M6). The measured data and UOA Model 3 predictions are shown in Figure 16.

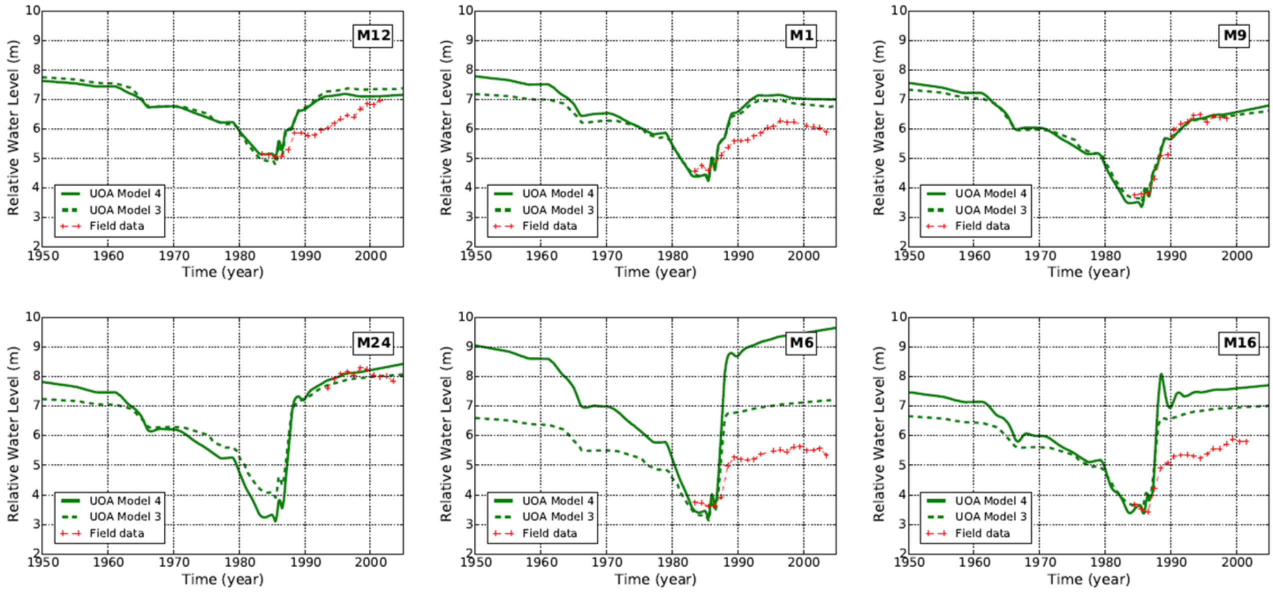


Figure 16: UOA Model 3 monitoring wells relative water level response to production.

In all cases the match is quite good though in most cases the model tends to predict a more rapid recovery than field measurements, especially in the vicinity of Whakarewarewa. Monitoring well M6 pressure match are neither satisfactory in UOA Model 3 nor UOA Model 4 and require further calibration including the impact of the nearby ICBF fault on the latter.

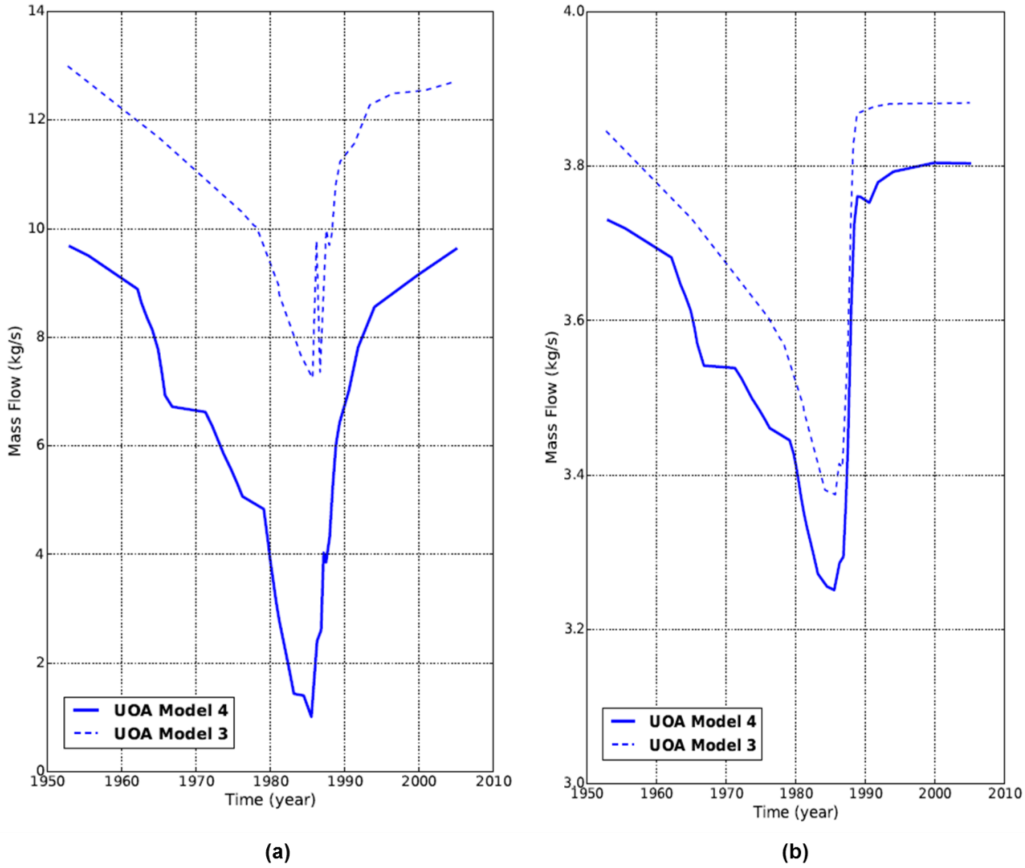


Figure 17 Surface mass flow evolution at: (a) Kuirau Park and (b) Whakarewarewa for UOA Model 3 and 4.

By 1988 the predicted model mass and heat flows have recovered to levels close to the natural state (Figure 15). This is consistent with the observations of 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.

The model predicts that by 2005 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 full 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 (UOA Model 3) and 78 MW (UOA Model 4) in 1990 which is a close match to the previously estimated figure of 77±20 MW (Glover, 1992).

UOA Model 3 and to a lesser extent UOA Model 4 underestimate the reduction of surface mass flow at Kuirau Park (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 (Figure 17 a).

Table 4: Surface features heat and mass flow.

Surface features	Date	Measured	UOA Model 3	UOA Model 4
Whakarewarewa Heat Flow (MW)	1950	300	266	245
	1967	228	251	230
	1985	158	228	205
	2000	>216	265	245
Whakarewarewa Mass Flow (t/d)	1950	34.560	29,300	33.540
Ngapuna Heat Flow (MW)	1990	77	85	78
Kuirau Park Mass Flow (t/day)	1986	0	1,200	780
	1993	1,728	1,573	1,426

8. NEXT STEPS

Temperatures and pressure drawdown are overall satisfactory when compared with the field data available; however surface mass and heat flow of geothermal features still need calibration and require additional data points to further constraint the model.

The horizontal and vertical refinement of UOA Model 3 has been effective for the overall representation of the lateral flow of geothermal fluid however it could not account for some of the fine-scale mechanisms. Particularly for some wells located within the same model block that show very different behavior: upflow, lateral flow or cold lateral flow. It was especially true for blocks at the edge of the geothermal reservoir and close to surface features where more accurate predictions required a horizontal refinement of the grid. UOA Model 3 was further refined horizontally to address these issues as well as vertically to allow more accurate representation of the water table. UOA Model 4 helps in matching abrupt temperature inversions seen in some wells as well as having a water table closer to actual levels. However more work is still needed to improve the matches to shallow pressures within the reservoir and transient response to the exploitation of the system (Monitoring well M6).

Given the large chemical data array of springs and wellbores collected throughout various campaigns, modeling of the RGF which includes chloride concentration and CO2 flux (e.g. with EWASG) may be relevant (Pruess, 1991) and further increase confidence in the modelling work.

9. CONCLUSIONS

Two new models of the Rotorua geothermal field have been developed that represents the shallow unsaturated zone and explicitly includes important structures identified in the conceptual model. The models, UOA Model 3 and 4, give 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 individual 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.

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

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