Modelling the Rotorua Geothermal System

John Burnell[1] and Paul Scholes[2]

[1]GNS Science, P.O. Box 30-368, Lower Hutt, New Zealand

[2] Bay of Plenty Regional Council Toi Moana, PO Box 364, Whakatāne 3158, New Zealand

j.burnell@gns.cri.nz

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ABSTRACT

The Rotorua Geothermal Field is an area of major geyser activity in Aotearoa New Zealand. The field was subjected to extraction of geothermal fluid by hundreds of households for heating and other purposes from the 1950's. After the decline of some of the thermal features was recognised in the mid-1980's an extensive monitoring programme was developed to provide an understanding of the system dynamics. Many aspects of that monitoring programme continue through to the current day including pressure and temperature monitoring. The Bay of Plenty Regional Council are currently undertaking a review of the Rotorua Geothermal Plan. Alongside of that review an update of a numerical reservoir model that was developed in 2004 has been carried out.

One of the challenges with modelling the Rotorua system is that very few wells have been drilled to more than 200m. As a consequence, the data is strongly biased towards the shallow parts of the system. In this paper we will use new data from Rotorua and information from other producing geothermal systems to inform a conceptual model that incorporates the deeper reservoir at Rotorua. We will also present a review of monitoring data collected at Rotorua, describe the conceptual model and the updated numerical reservoir model.

1. INTRODUCTION

The Rotorua Geothermal Field has several unique characteristics. It underlies a city and contains one of New Zealand's last remaining areas of major geyser activity at Whakarewarewa – see Figure 1. The geysers are considered to be of regional and national significance, and all geothermal features have strong social, cultural and economic value. From 1950 the field was subjected to a period of intensive fluid withdrawal, with over 900 shallow wells drilled. As a result the field pressures declined along with surface activity (Lloyd 1979; Cody and Lumb 1992).

Concern over the decline of some of the geysers and hot springs at Whakarewarewa led to the establishment of the Rotorua Geothermal Monitoring Programme (RGMP) in 1982. In addition, a Task Force was set up to measure the level of drawoff from wells, amongst other things. In the winter of 1986, aquifer pressures had fallen to the lowest levels since the monitoring programme began. A recommendation was made to the Government that urgent action was required to prevent further deterioration of geyser activity. As a result, the Government ordered a closure of all wells within a 1.5 km radius of Pohutu Geyser (Figure 1) and introduced a charging regime for extracting geothermal fluid from the field (the Bore Closure Programme).

The Bay of Plenty Regional Council (BOPRC) assumed responsibility for managing the field in the 1990's under the Resource Management Act (1991) and the Rotorua Geothermal Regional Plan was made operative in July 1999. The key objective of the plan is to protect and bring about recovery of geothermal surface features while providing allocation for various uses.

This paper describes recent modelling and analysis of monitoring data undertaken to support a review of the Rotorua Geothermal Plan.

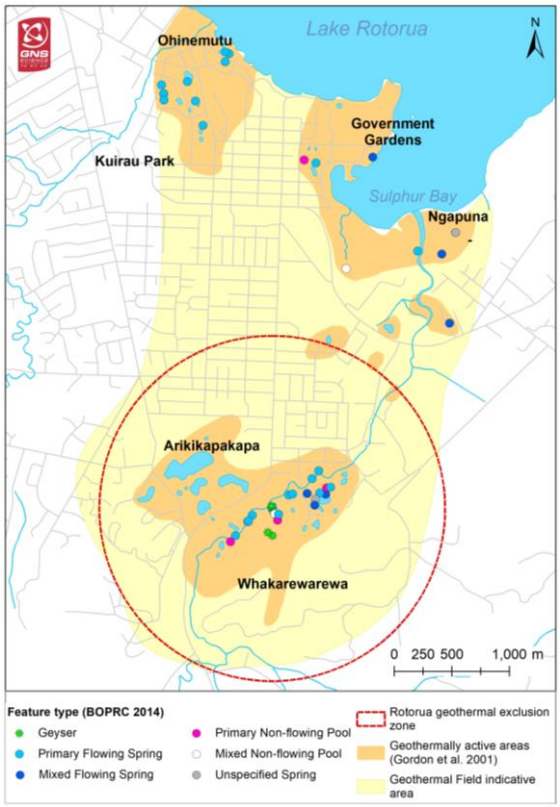

Figure 1: Map showing the extent of the Rotorua Geothermal System and currently monitored surface features (adapted from Scott et al. 2021). Pohutu geyser is located at the centre of red exclusion zone.

1.1. Background

The Rotorua Geothermal System, like other geothermal systems in the Rotorua-Taupo area, is a by-product of large-scale volcanism and rifting. The Rotorua Geothermal System has surface manifestations that range from geysers and hot springs to mud pools and warm ground. These areas are shown in Figure 1.

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The Bore Closure Programme of 1987/88 resulted in a reduction of the net withdrawal from the system from around 31,000 tonnes/day in 1985 (Drew et al. 1985) to 5,500 tonnes/day in 1990, with production from the system reduced by about 60%. In turn this saw an immediate increase in reservoir pressures. Between 1988 and 1991, pressures further increased (Bradford 1992; Burnell 1992) and a recovery of some surface features began to be observed (Cody and Lumb 1992).

As a result of these events, the Rotorua Geothermal System was the subject of considerable scientific study in the 1980s–1990s. The results of the RGMP were summarised by the Ministry of Energy (Mahon 1985). More information was presented in a special issue of Geothermics (Allis and Lumb 1992 and references within). Summaries of monitoring by the BOPRC were presented by Hodges (1998), Grant-Taylor and O'Shaughnessy (1992) and Gordon et al. (2001, 2005). Scott and Cody (2000) and Scott et al. (2005) described and discussed aspects of the recovery of surface features, and a current overview of the system data is presented in Scott et al. (2021).

Two previous versions of a Rotorua geothermal reservoir model have been developed for BOPRC – Burnell and Young (1994) and Burnell and Kissling (2005). While both those models were satisfactory at the time of development, expectations related to model construction and the match to measured data have evolved leading to an update of the 2004 model which is described later.

2. CONCEPTUAL MODEL

A conceptual model for the Rotorua Geothermal System was formulated and refined by many researchers in the 1980s (the 1980s conceptual model). This conceptual model was based on the large amount of information collected and presented in several publications including Mahon (1985), Allis and Lumb (1992), Grant-Taylor and O'Shaughnessy (1992) and Gordon et al. (2001).

The 1980s conceptual model focussed on the shallow part of the Rotorua Geothermal System in which wells had been drilled (to a depth less than 400 m). The model provided little insight into the characteristics of the system at deeper locations.

Since this conceptual model was developed, new data has been collected and new studies have been performed at Rotorua including:

- Magnetotelluric (MT) data that has been collected and inverted to estimate electrical conductivity (Heise et al. 2016).
- A 3D geological model of the Rotorua Geothermal field developed by Alcaraz (2014).
- Continued monitoring of surface feature activity (Scott et al. 2021).
- Continued monitoring of water levels (Scott et al. 2021).
- Downhole temperature measurements (Scott et al. 2021 and Austin 2017).
- A heat flow survey conducted in 2018 (Seward et al. 2018).
- Measurements of well flow rates (Laurent 2019).

In addition to these direct measurements at Rotorua, new geothermal developments have been undertaken at Kawerau (Askari et al. 2015), Rotokawa (Hernandez et al. 2015), Ngatamariki (Boseley et al. 2010) and Ngawha (Burnell et al. 2016) which have provided additional insights into the structure of New Zealand's geothermal systems. Common features of these systems include a coherent low permeability caprock that sits above the reservoir with temperatures at the top of the reservoir in the range 200–220°C. The caps have discrete locations where fluids pass through from the deeper reservoir. Above the cap the hot geothermal fluids mix with flowing groundwaters in a reservoir often called an Intermediate Aquifer (Boseley et al. 2010).

Based on this new data and insights, we have extended the conceptual model of the Rotorua geothermal system to incorporate deeper parts of the system that are below drilled depths. It is this conceptual model that was used as the basis for the geothermal reservoir model presented here.

Intermediate aquifers (Boseley et al. 2010 and Hernandez et al. 2015) are confined aquifers with temperatures between 50 and 180°C. As these are the conditions that have been drilled at Rotorua, it is postulated that the current production aquifer at Rotorua is an intermediate aquifer and not part of the deeper geothermal system.

2.1. Resource Boundary

The geothermal system boundary has been inferred from electrical resistivity measurements (Bibby et al), shallow temperatures and locations of surface features and is shown in Figure 1. This boundary encompasses an area of approximately 20 km^2. The vertical extent of the system is uncertain as the deepest wells are less than 400 m in total depth.

2.2. Geological Structure

Three main geological formations have been identified in the shallow portions of the Rotorua Geothermal System, being sediments, the Rotorua Rhyolite and the Mamaku Ignimbrite which are illustrated in Figure 2. The rhyolite and ignimbrite formations comprise the main aquifer from which wells produce hot fluid, being identified by Wood (1985) as providing good permeability, especially near the surface.

A number of faults have been identified in the system, and some are believed to provide permeable paths for the upflow of deep hot fluid.

2.3. Reservoir Pressures

An analysis of historical reservoir pressures was undertaken by Grant et al. (1985). They identified a small number of reliable data points from before large-scale extraction of fluid occurred. The data shows higher pressures in the south decreasing near the lake.

Figure 3 shows contours based on estimates of the reservoir pressures at a reference level of 180 masl. in 1985. Both the initial pressures and those of 1985 show a pattern of higher pressures in the south and east and lower pressures near the lake. This indicates a flow of fluid in the intermediate aquifer towards the lake.

2.4. Reservoir Temperatures

The reservoir temperatures are more difficult to derive from downhole temperature profiles than the pressures. Although a large number of temperature profiles have been measured, the state of the well was not always recorded. Iles (1982) and Wood (1985) have previously studied the Rotorua

temperature data and presented contours of temperatures at 180 masl. For this work we have re-examined the temperature data to identify profiles that are representative of pre-exploitation conditions.

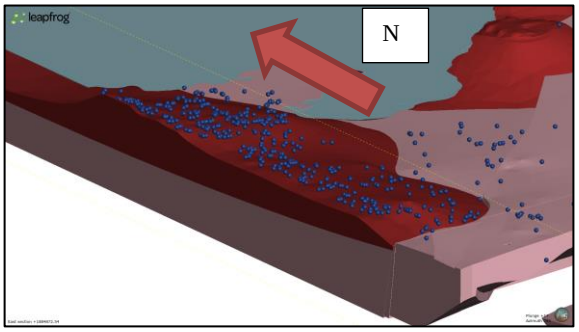

Figure 2: 3D Rotorua geological model (Alcaraz 2014) showing the Rhyolite (brown) and Mamaku Ignimbrite (pink) formations. The blue spheres are wellheads and the blue region is Lake Rotorua.

Examples of these pre-exploitation temperatures are shown in Figure 4. Also shown are temperature profiles from monitor wells measured in 1991 (Figure 5), and temperature contours at 180 masl taken from data measured up to 1985 (Figure 6). From the temperature data we observe:

- Boiling temperatures are present in the vicinity of the Whakarewarewa area, south of Government Gardens and in the Ngapuna area.
- In the centre of the reservoir, temperature inversions are present, indicating that cooler water is flowing across the system between 50 and 100 m depth.
- Temperatures in the west are generally lower than in the east.
- Only four bores have measured temperatures above 200°C. Three are in the Ngapuna area and one near Whakarewarewa.

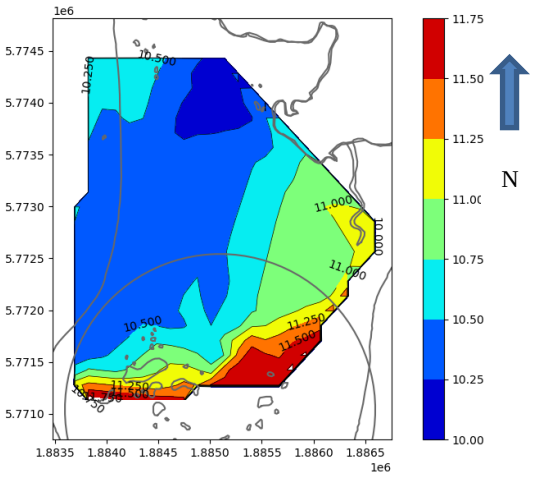

Figure 3: Contours of measured pressures (bars) at 180 masl. in 1985 after Grant et al. (1985).

An important observation can be made from the temperature data. The thermally altered low permeability caprocks usually have temperatures at the base of the cap of around 220°C (Gunderson et al. 2000). This suggests that the base of the cap at Rotorua has an elevation of around 50 masl. Thus, the drilled wells provide no direct information about the properties of the deeper geothermal reservoir.

2.5. Inflows and Outflows

MT data from Heise et al. (2016) show regions of low conductivity below Whakarewarewa at depths greater than 3500m. This could indicate the location of the heat source for Rotorua.

There are three main areas of outflow from the Rotorua Geothermal System, which are expressed as surface thermal feature activity. This activity is found at Kuirau Park/Ohinemutu, and Government Gardens/Ngapuna and at Whakarewarewa/Arikikapakapa as shown in Figure 1.

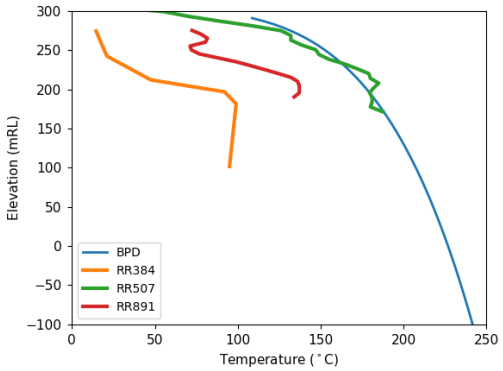

Figure 4: Measured pre-exploitation temperature profiles from the southern portion of the Rotorua reservoir. The blue curve shows the boiling point for depth profile.

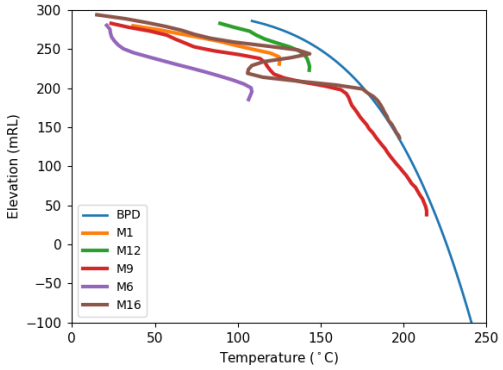

Figure 5: Measured temperature profiles from Rotorua monitor wells taken in 1991. The blue curve shows the boiling point for depth profile.

Measurements of heat flows from the thermal areas have been made by different groups (Lloyd 1969 (unpublished results summarised in Cody and Simpson (1985).), Cody and Simpson 1985 and Seward et al. 2018). These heat flow surveys have included different areas of the system, but all have included the Whakarewarewa area. Summaries of the measurements from these surveys are given in Table 1. However, the data from these surveys are not directly comparable with each other as they have measured different features in the thermal areas.

To account for these differences in methodology the data has been analysed to provide ranges of heat flows that can be compared at different times. These ranges are not estimates of uncertainty, but a mechanism to make the surveys comparable. These ranges are shown in Figure 7.

In addition to these measurements, Glover (1992) presented an estimate of the heat flow from the Ngapuna area of 77 MW and Seward et al. (2018) have measurements from Arikikapakapa and Kuirau Park (Table 2).

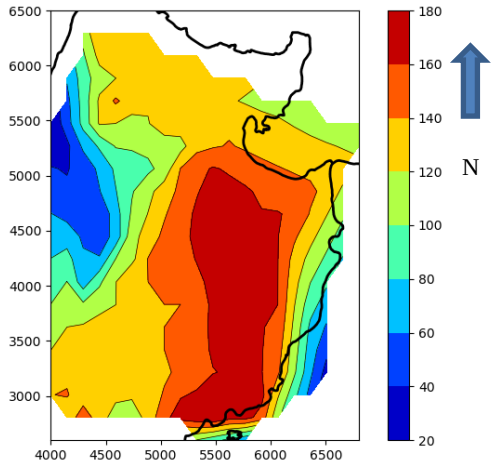

Figure 6: Contours of measured temperatures at 180 masl. from the early 1980s after Wood (1985).

Table 1: Summary of heat flow measurements from Rotorua.

Area	Survey Date		
	1969 Lloyd	1985 Cody and Simpson	2018 Seward et al.)
Whakarewarewa	145 MW	141 MW	144 MW
Arikikapakapa	-	-	72 MW
Kuirau Park	-	-	73 MW

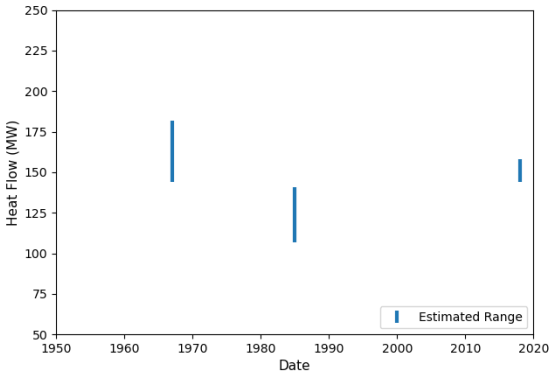

Figure 7: Ranges of heat flow measurements at Whakarewarewa for the three surveys in 1969, 1985 and 2018.

Table 2: Measured heat flows from other areas in Rotorua. The data for Ngapuna is taken from Glover (1992) and Kuirau Park and Arikikapakapa are from Seward et al. (2018).

Area	Date	Heat Flow (MW)
Ngapuna	1992	77
Kuirau Park	2018	73.4
Arikikapakapa	2018	72

2.6. Response to Production

Quantifying the changes that have occurred in the Rotorua system since production started is not a straightforward task. There are limited measurements from the system prior to the start of production, and details of extraction rates have high uncertainties.

There are measurements of changes in monitor bores in response to the 1987/88 Bore Closure Programme, Gordon et al. (2005) and Scott et al. (2021), provides important calibration data for the reservoir model. However, the details of the changes in extraction rates that caused these pressure changes are poorly understood, bringing some uncertainty as to the cause of changes in monitor bore data..

Monitoring of pressure in the Rotorua Geothermal System was started in 1982. Bradford (1992), Kissling (2014) and Scott et al. (2021) have presented summaries of water level changes in these monitor wells. Examples of this data is shown in Figures 8 to Figure 9.

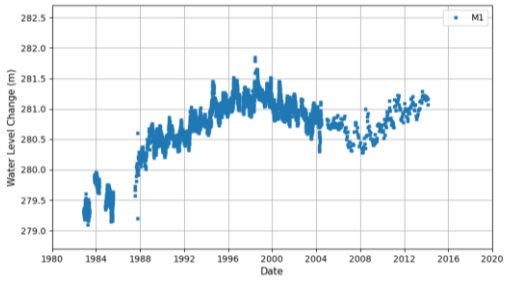

Figure 8 Measured water levels for M1.

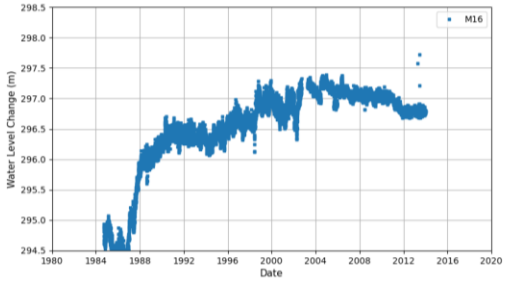

Figure 9 Measured water levels for M16.

From this data a number of features are immediately apparent:

- Water levels were lower and were decreasing before the 1987/88 Bore Closure Programme.
- Between 1987 and 1988 all well measurements showed significant increases in water level.
- Further increases were seen between 1990 and 1995.
- After the mid-1990 there are long term cyclical patterns of water level increases and decreases.

A comparison of water levels at Rotorua with other bores in the area show a consistent response to atmospheric pressures. In addition, Scott et al. (2021) also suggest that the longer-term water level variations are influenced by rainfall. These factors suggest that there are changes in water level that are not related to extraction from the system.

2.7. Changes in Fluid Extraction

It has not been possible to obtain a reliable record of extraction changes in the Rotorua reservoir over the period of

extraction. At a few times, estimates have been made of the rates of extraction.

Measurements were made by the Rotorua Geothermal Task Force (Drew et al. 1985) between 1983 and 1985. Measurements were made from 406 bores that were known to be active. This provided estimates of extraction of between 31,000 tonnes/day in the winter and 25,000 t/d in the summer for the period 1983–85.

As a record of bores that were closed during the Bore Closure Programme was kept, the reduction in total extraction that occurred during this period is also known. But details for individual bores have not been found. The estimated total extraction rate after 1990 was 11,000 t/d.

After responsibility for the management of the Rotorua field passed to the BOPRC in 1991, extraction of geothermal fluid required a resource consent. This has provided a record of known extraction and reinjection bores together with the maximum extraction allowed for each well. Finally, in 2017, measurements in a small set of bores were undertaken by the BOPRC.

From these various data sets, estimates of the total production and reinjection from the Rotorua Geothermal System have been made, and these are shown in Figure 10.

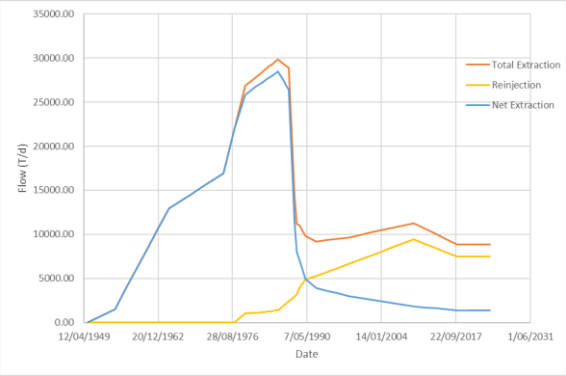

Figure 10: Estimated production rates at Rotorua

2.8. Conceptual Model Summary

From the analysis of the data presented in this section, a conceptual model of the Rotorua system is postulated. This model builds on 1980s Rotorua conceptual model with new features focussed on the deeper portion of the Rotorua Geothermal System:

- A low permeability cap with a base around 50 masl.
- Above the cap (around 100 masl) is an intermediate aquifer from which most of the extraction has occurred.
- Above the intermediate aquifer is a shallow groundwater aquifer.
- In the south of the reservoir a deep heat source provides upflowing hot fluid that ascends along the southern boundary of the Rotorua caldera.
- There are holes in the cap near the areas of surface thermal activity at Whakarewarewa/ Arikikapakap, Kuirau Park/Ohinemutu and Ngapuna/Government Gardens. This is postulated from the temperature and chemistry distribution and inversions in temperature profiles.
- In the intermediate aquifer there is a flow of geothermal fluids towards the lake, mixing with cold groundwater in the west.

These features are summarised in Figure 11.

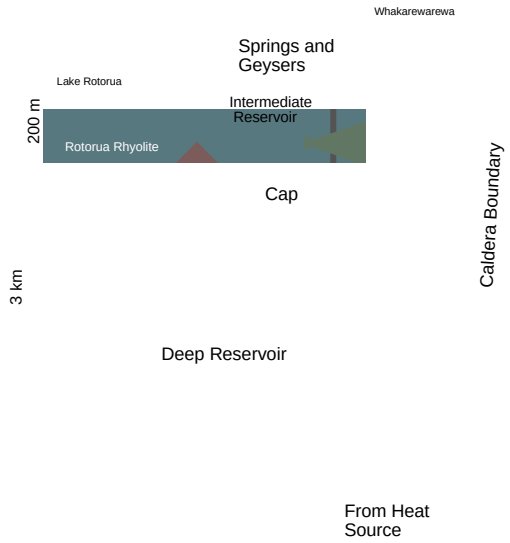

Figure 11: Schematic illustration of the key aspects of flow from the Rotorua conceptual model in the deep and intermediate reservoir. The red arrows represent flows of hot geothermal fluids.

3. ROTORUA RESERVOIR MODEL

The 2021 Rotorua geothermal reservoir model was developed as a dual porosity TOUGH2 model using the EOS2 module (Pruess et al. 1999) – which models the flow of water, CO_2 and energy. CO_2 is included in the model as studies such as Werner and Cardellini (2005) show areas of high heat flux (>11,000 g m^{-2} d^{-1}.

The model is based on a grid built from 19 identical horizontal layers, each with 1064 elements and covers an area of 10.7 by 12.7 km. A horizontal layer from the model grid is shown in Figure 12. Vertically the model extends from the ground surface (280 masl at Lake Rotorua) down to -2000 masl.

3.1. Boundary Conditions

The only boundary conditions are set at top of the model. The atmosphere is represented by a boundary condition with values of pressure at 1 bar abs., a temperature of 17°C and a CO_2 partial pressure of 0.999 bar abs. In addition, the water bodies of Lake Rotorua and Puarenga Stream are represented by liquid boundary conditions of 1.9 bar abs and 17°C.

3.2. Sources and Sinks

A hot upflow is applied to the base of the model underneath the Whakarewarewa area. It is comprised of 520 kg/s of 1,250 kJ/kg fluid, which was derived by adjustment during the development of the model to match measured temperatures and surface heat flows.

On the top surface of the model, a source was added to represent an annual rainfall of 1.3 m with an infiltration rate of 7.5%.

3.3. Spring and Geyser Model

The springs and geysers at Rotorua were represented as model sinks by placing wells on deliverability (Pruess et al. 1999)

into appropriate grid blocks. The locations of modelled surface features at Whakarewarewa, Kuirau Park, Ngapuna and Government Gardens are shown in Figure 1.

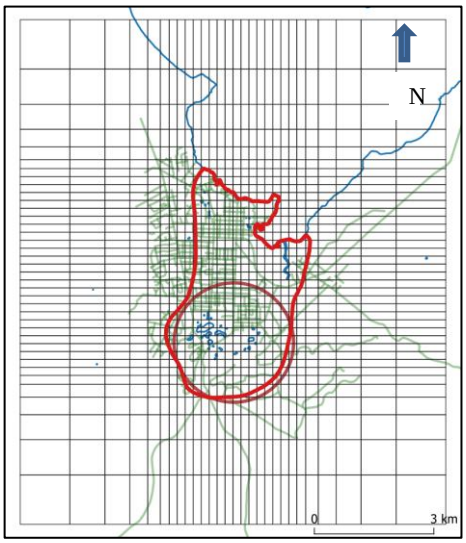

Figure 12: Plan view of grid used for modelling the Rotorua Geothermal System. The light green curves are roads.

3.4. Model Rock Properties

Features of the rock types represented in the model are: very permeable shallow rhyolites and sediments; a low permeability cap that extends from 50 masl to 100 masl with holes of higher permeability under thermal areas; below the cap are moderate to low permeability Rhyolites and Ignimbrites.

The physical properties of the model's rocks (permeability, porosity and thermal conductivity) were adjusted to obtain acceptable matches to measured data.

4. MODEL RESULTS

The model was used to simulate both the natural state and the response to extraction from the reservoir. Model results were compared to measured data: temperatures before extraction started; pressure changes since extraction started; and measured heat flows.

4.1. Natural State

Model temperatures are compared to temperatures measured prior to 1970 in Figure 13. Also shown in Figure 14 are a comparison of the model temperatures in 1991. Generally, the model temperatures are a good match to measured profiles. Some of the model temperatures in the centre of the system are hotter than observed, so there may not be enough mixing with surrounding groundwater in the model.

4.2. Response to Production

Estimated extraction rates shown in Figure 10 were input into the model and the reservoir response was simulated until 2020.

4.2.1. Pressure Response

Model results were compared to measurements of pressures that are reported as water levels. The comparison was done using water levels calculated by estimating a suitable density to apply to the model pressures. This comparison is illustrated in Figures 15 and 16 for two monitor bores. The plotted water level change is relative to levels in 1985.

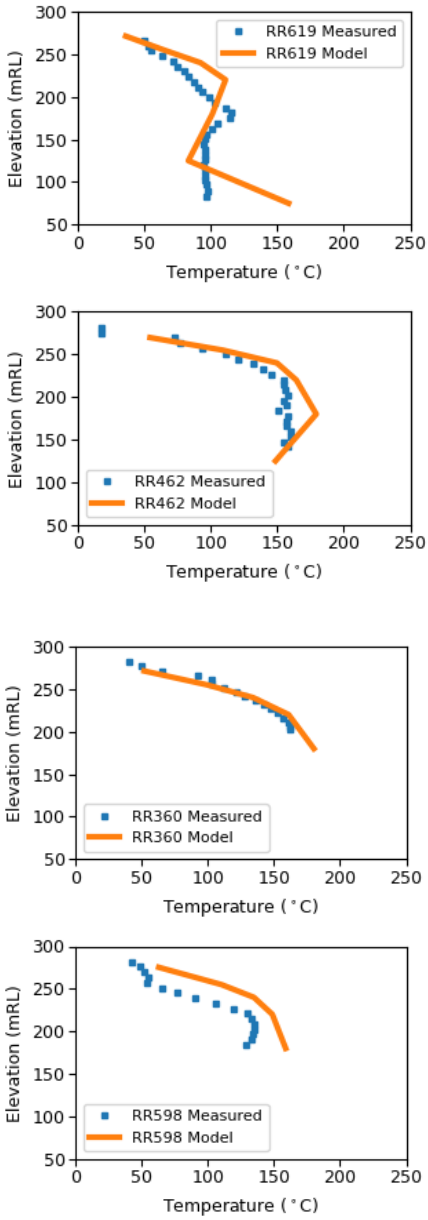

Figure 13: Comparison of measured and modelled natural state temperatures for the central wells RR619, RR462, RR360 and RR598.

The model only considers changes in water levels that result from extraction from the system. However, as discussed in Section 2.6 there appear to be changes in water level that are unrelated to extraction from the reservoir. This includes annual variations in water level of approximately 0.5 m.

Generally, the model reproduces the changes in pressure observed as a result of the Bore Closure Programme. With uncertainty regarding the detail of extraction, this level of match to pressure changes is considered to be acceptable.

4.2.2. Heat Flows

In addition to comparing pressure changes, changes in heat flow were also considered. As discussed in Section 2.5, to compare measured heat flows at Whakarewarewa at different times the ranges of heat flows need to be considered. Heat

flows were calculated from the spring and geyser model sinks and conductive heat flows from the surface blocks. Comparisons of modelled heat flows with these ranges of measurements are shown in Figures 17 and 18. Within the measurement ranges there is an acceptable agreement with the model results.

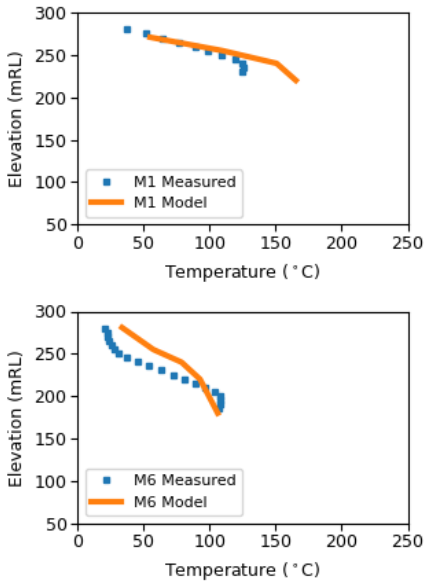

Figure 14: Comparison of measured and modelled temperatures in 1991 for monitor wells M1, and M6.

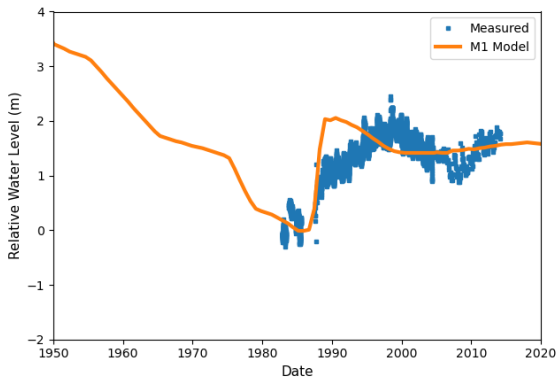

Figure 15: Comparison of modelled and measured relative water level changes in M1.

4.3. Comparison with Previously Models

Previous reservoir models of Rotorua have been developed by Burnell and Kissling (2005) and a group at the University of Auckland (Dekkers et al, 2020 and Ratouis et al, 2016). Compared to Burnell and Kissling the 2021 GNS model now includes a deep reservoir covered by a clay cap. The match of the 2021 GNS model to measurements from the system is slightly improved from the 2005 model.

Compared to the University of Auckland (UoA) model the conceptual model is different. The UoA model has 3 separate deep upflows at different temperatures, whereas the 2021 GNS model has a single upflow zone. The UoA model has a clay cap that extends from -700 masl to the surface compared to the 2021 GNS model where the clay cap is located between 50 and 100 masl. The base of the clay cap typically corresponds to a temperature of approximately 220 °C. Based on temperature profiles where 218 °C has been measured at a depth 50 masl, -700 masl would appear to be too deep for the base of the clay cap.

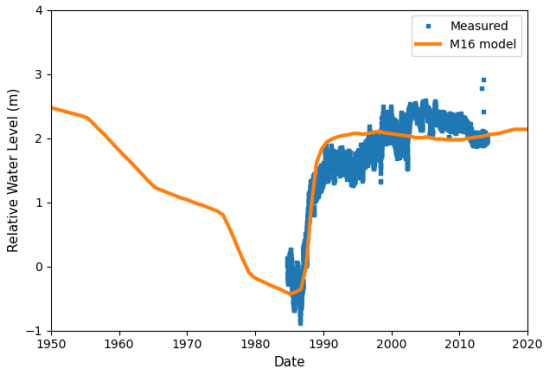

Figure 16: Comparison of modelled and measured relative water level changes in M16. The light green curve is the relative MGAWL.

5. SUMMARY

An updated conceptual model of the Rotorua Geothermal System has been presented, which incorporates data collected since the 1990s together with understandings from other geothermal systems in Aotearoa New Zealand. together with a description of a reservoir model of the field. This formed the basis of an update of the Rotorua geothermal reservoir model, which continues to provide acceptable matches to data measured from the system.

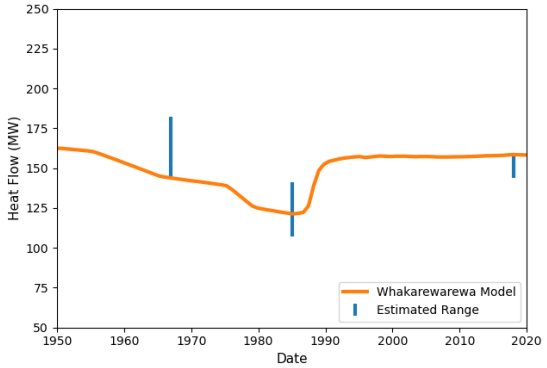

Figure 17: Comparison of measured and modelled heat flows for the Whakarewarewa area. The use of a range of heat flow for the measured data is explained in Section 2.5.

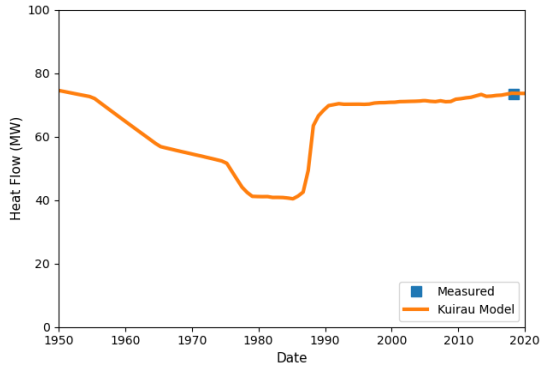

Figure 18: Comparison of measured and modelled heat flows for the Kuirau Park area.

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