Industrial Research Limited Report

Rotorua Geothermal Reservoir Modelling Part 1:
Model Update 2004

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1   Executive Summary

A computational model of a geothermal system is a tool that can predict pressures, temperatures and flows within and out of the system. It can be used to predict the effects of production and reinjection on the geothermal resource and surface activity. A model needs to represent the key features which control fluid flows in the geothermal system. Development of a model requires calibration against field measurements from the system.

An update was undertaken of the 1994 computational model of the Rotorua geothermal field to ensure that it conforms to current state-of-the-art geothermal modelling practices and to check model performance with recent field data.

The conceptual model of the Rotorua geothermal field was first reviewed in light of field data collected between 1994 and 2004. This new data did not suggest any significant changes to the conceptual model.

The computational model was then updated to improve the representation of the conceptual model. The changes resulted in a more accurate representation of the geological formations and the boundary conditions that influence the field. This new computational model was calibrated against pressure, temperature and heat flow measurements made between 1967 and 1992. The model results were then compared to data collected between 1992 and 2004. Generally the model gave a good match to changes observed in the system since the Bore Closure Programme started in 1986.

The model is a suitable tool for predicting the response of the system to changes in production and reinjection strategies. It will be used to predict the likely impact on surface features of new productions scenarios that are being considered by Environment Bay of Plenty as part of the review of the Operative Regional Management Plan. The results of that work will be reported in Part 2 of this report.

2 Introduction

This report is the first of two reports that describe the results of recent computational modelling of the Rotorua geothermal field. This work was commissioned by Environment Bay of Plenty to support the review of the Operative Regional Management Plan. This report describes the updated computational model of the Rotorua Geothermal field and a second report presents the results of 19 scenarios for possible future production.

The reservoir model described in this report was originally developed in 1994 and is described in the report by *Burnell and Young (1994)*. The scope of this work was to update the model to:
- Ensure it conforms with current state-of-the-art geothermal modelling practices;
- Compare model predictions to the actual field data collected to 2004;
- To identify any disparities between model predictions and the validation data and provide explanation as to the differences;
- Discuss whether the field has reached a new equilibrium in terms of field mass and heat which meets the original model predictions or whether there are changes in field recovery that do not meet model predictions or that are outside of model tolerances.

The 1994 model provided a satisfactory fit to the available data but it is now timely to review that model in light of improvements in the state-of-the-art technology for modelling geothermal systems. Improvements in computer hardware and software capability have now made it possible to develop and solve larger and more complex models. The ability to produce more complex models can enable a more accurate representation of the very complex conditions that are usually associated with geothermal fields.

In addition to advances in geothermal modelling capabilities, there is now a longer record of data for the Rotorua geothermal field available for comparing to model results. Much of this new monitoring information is summarised in the report by *Gordon et al (2001)*. The consequences of this new data on the understanding of flow patterns and processes in the system have also been considered in this work.

It is not the purpose of this report to review all the previous work on the Rotorua geothermal field, as this has been presented in the following publications:
- *The Rotorua geothermal field.* Technical report of the geothermal monitoring programme 1982-1985, Ministry of Energy, hereafter referred to as *RGMP (1985)*,
- *Rotorua Geothermal Field, New Zealand.* Special Issue **Geothermics**, 1992, Vol. 21, No. 1
- Bay of Plenty Regional Council *Rotorua Geothermal Field Response of Field Since Closure (1987-1992),* hereafter referred to as *Grant-Taylor et al (1992),*
- *Rotorua Geothermal Field Management Monitoring*, Environment Bay of Plenty Report 2001/22, hereafter to as *Gordon et al (2001)*.

However, in order to facilitate reading of this report, some of the key results will be summarised during the report. As this report is to be used to support the review of Environment Bay of Plenty's Regional Management Plan many readers will not be geothermal experts. Therefore the report is presented in 2 parts: the first part provides a general overview of the model and the results; and the second part presents the technical details of the work as an appendix.

3   The Modelling Process

A model of a geothermal field calculates the state of the field (pressure, temperature, outflows) in response to events such as production and reinjection. The development of a model consists of two stages:

1. Developing a conceptual model. The conceptual model is our understanding of the key structures and processes of the geothermal field that influence the flow. It is developed from data and observations relating to the field.

2. Developing and running a computational model. The computational model is a representation of the conceptual model in a form suitable for use with a computer program called a geothermal simulator.

The stages involved in developing a reliable and predictive computational model are:

1. Construct initial conceptual and computational models
2. Solve the model using a geothermal simulator to calculate temperatures, pressures and flows
3. Compare model results with measurements from the natural state, and the response to production
4. Refine the model parameters to improve the comparison in stage 3
5. Repeat stages 2-4 until a satisfactory match is reached in stage 3

These stages are illustrated in Figure 1.
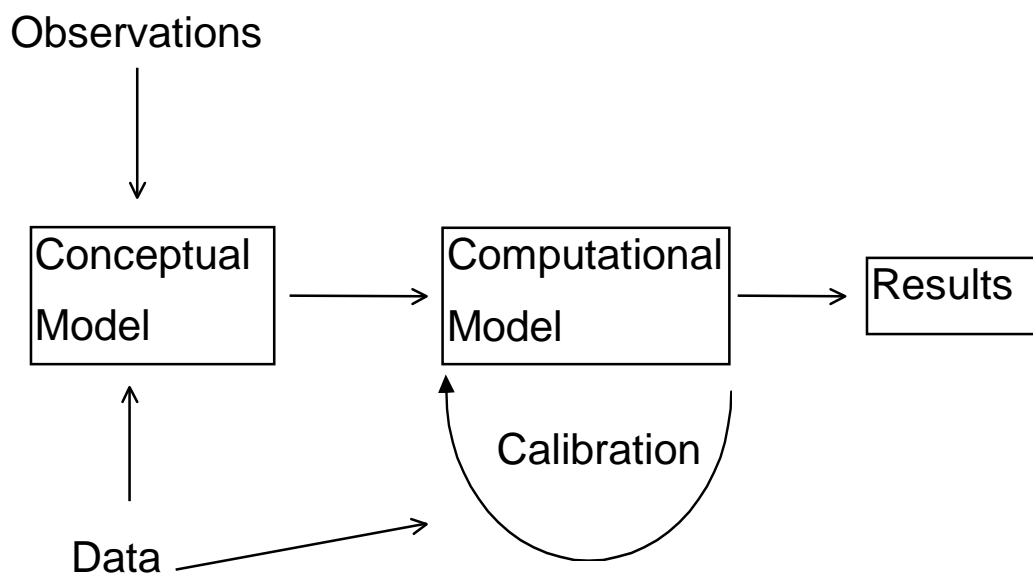
Figure 1: Flowchart showing the modelling process

4   Conceptual Model of the Rotorua Geothermal Field

Our computational model is a representation of the conceptual model of the Rotorua geothermal field. The conceptual model is our understanding of the key features of the field that influence the flow and the response of the geothermal system.

The conceptual model for the Rotorua geothermal field has been formulated and refined by many researchers. The current conceptual model is based on the large amount of information that has been collected by a number of organisations: the Bay of Plenty Regional Council, the former Department of Scientific and Industrial Research, and central Government Ministries. This data has been presented in a number of publications including *RGMP (1985), Geothermics (1992), Grant-Taylor et al (1992)* and *Gordon et al (2001)*. To assist the reader, some of this data is summarised in Section 11 of the Appendices.

The conceptual model for the field was developed by considering all the available data and information and forming a consistent picture of the important structures and physical processes. This information and data includes:
- The geological structure;
- Electrical resistivity;
- Heat and mass flows from springs and streams;
- Fluid chemistry;
- Isotopic composition of fluid;
- Well temperatures;
- Regions where boiling occurs;
- Pressure and waterlevel data;
- Pressure changes in response to withdrawal;
- Temperature changes in response to withdrawal.

The key features of the Rotorua conceptual model are:
- A shallow geothermal aquifer;
- An overlying groundwater system;
- Geological formations including the Rhyolite Domes, Mamaku Ignimbrite and overlying sediments;
- Faults that influence the flow, including the ICBF, Roto-a-Tamaheke and Ngapuna Faults;
- Hot flows into the geothermal aquifer underneath Whakarewarewa, Pukeroa Dome, and along Puarenga Stream;
- Outflows in the form of springs or geysers at Whakarewarewa, Kuirau Park and Ngapuna;
- Interaction between rainfall and the geothermal aquifer;
- Surrounding groundwater which mixes with the geothermal waters;

The influence of these features on the geothermal system will be discussed in the following sections.

4.1   The Geothermal Aquifer and Groundwater System

The geothermal field encompasses an area of approximately 20 km^2 as defined by temperatures and electrical resistivity measurements and is shown in Figure 2. Wells drilled into the field have shown that the geothermal system extends to at least a depth of 500m. Although it is likely that the

geothermal system extends to a much greater depth, this has not been verified because no deep wells have ever been drilled. To date, most production wells are shallow wells drilled into the upper 300m of the field. Therefore most of the data relates to the shallow upper section of the field.

The focus of this work is the response of surface features to production and reinjection, and it is likely that flows to these surface features will be controlled by this upper shallow section of the field. For these reasons, the model is focussed on the shallow part of the field, but does include upflows that come from the deeper parts of the system.

Overlying the geothermal aquifer is a shallow groundwater system. There are some interconnections between the shallow groundwater aquifers and the geothermal aquifer. But most of the overlying groundwater is isolated from the geothermal aquifer. The groundwater laterally adjacent to the geothermal aquifer is known to interact with the hot geothermal system. For example, some cooling due to inflow of cold groundwater was observed in western rhyolite wells as a result of production from the field.

Figure 2: Extent of Rotorua Geothermal Field as defined by resistivity surveys. The map was provided by Environment Bay of Plenty.

4.2   Geological Structure

The two main formations that have been identified in the shallow portions of the geothermal system are the Mamaku Ignimbrite and the Rotorua Rhyolite as shown in Figure 3. These two formations comprise the main geothermal aquifer in which production wells are drilled. The ignimbrite and rhyolite formations are overlayed by sedimentary formations that confine the geothermal fluid. *Wood (1992)* has developed contours of top surface of the rhyolite domes and these are shown in Figure 4. A number of faults have been identified in the field, and some are believed to provide permeable paths for the upflow of deep hot fluid. Figure 5 shows the influence of the faults postulated by *Simpson (1985)*.

The intrinsic properties of geological formation provide the ability for geothermal fluid to be stored and transported. The ignimbrite and rhyolite formations have been identified by *Wood (1985)*, as providing good permeability, especially near the surface. The rhyolite formations of the field have been found to be very permeable and transport fluid very quickly.
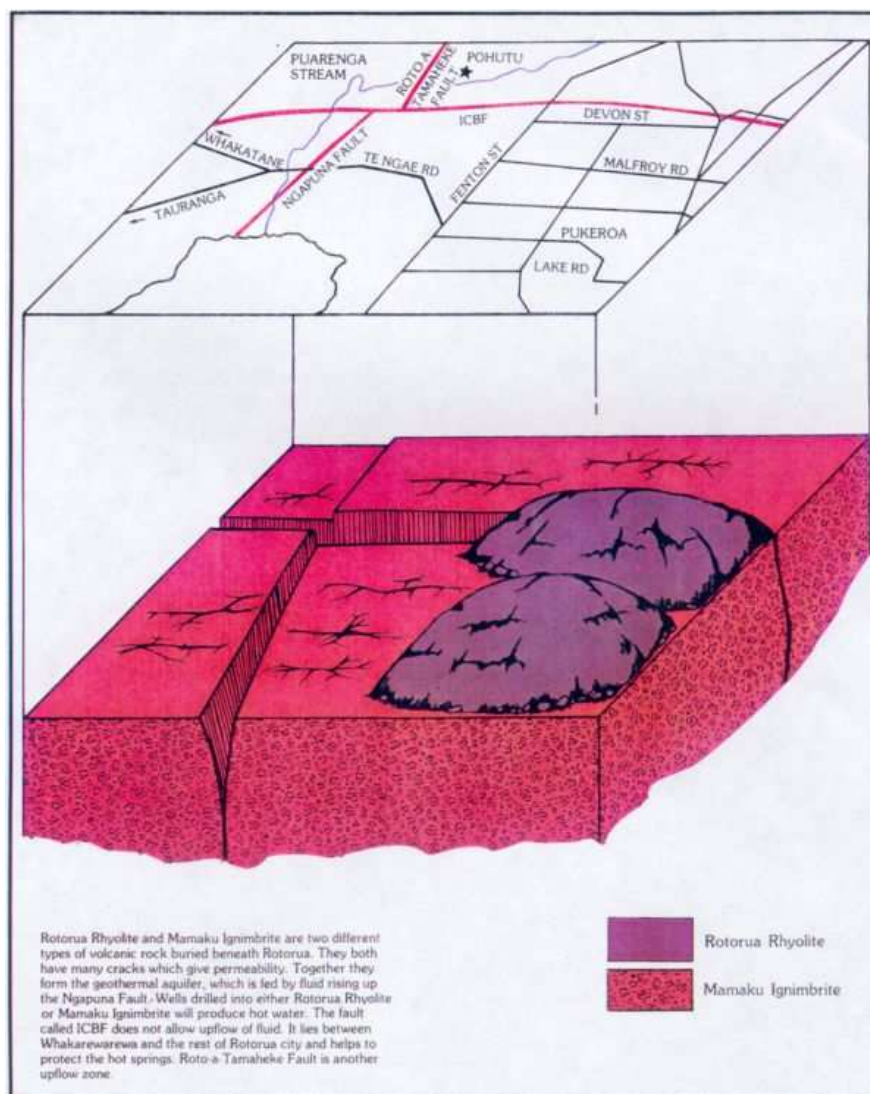
Figure 3: Diagram showing major geological and structural features. The diagram is taken from Gordon et al (2001).

Figure 4: Contours of the surface of the rhyolite domes from Wood (1992).

Figure 5: Inferred influence of faults from Simpson (1985).

4.3   Inflows and Outflows

There are three main known areas of outflow from the field, which are expressed as surface feature activity. Thermal activity is found at Kuirau Park/Ohinemutu, and Government Gardens/Ngapuna in the north and Whakarewarewa/Arikikapakapa in the south as shown in Figure 6. It is likely that there are further outflows into and under Lake Rotorua (*Mongillo and Bromley (1992), Whiteford (1992)*). Inflows into the field have been inferred from the pressure and temperature measurements and the fluid chemistry. Figure 7 shows a schematic diagram of these inflows.

Figure 6: Areas of surface activity at Rotorua, taken from Gordon et al (2001).
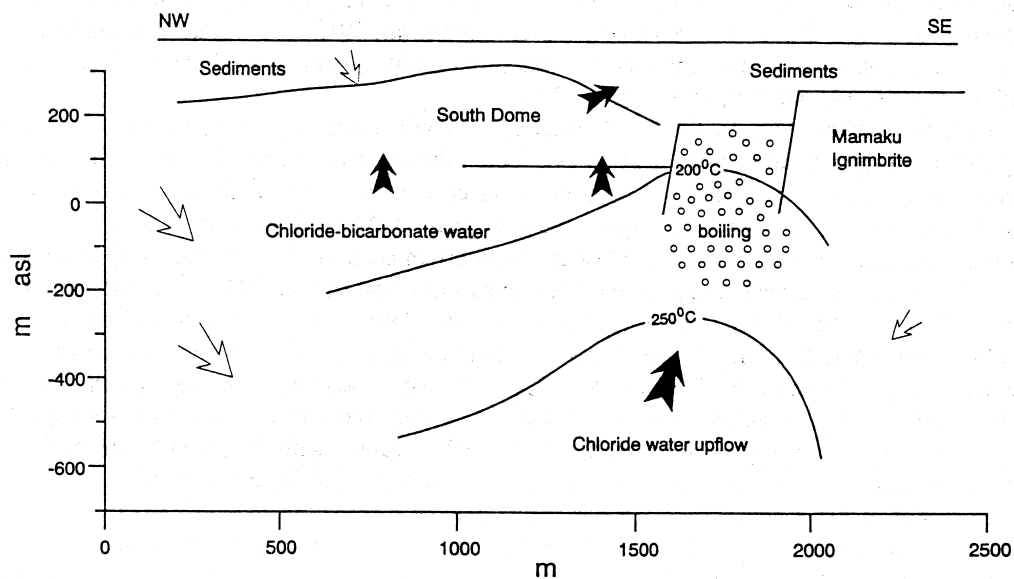
Figure 7: Schematic illustration of inferred upflows from Stewart et al (1992). The black arrows represent flows of hot geothermal fluid and the white arrows are groundwater flows.

5   The 1994 Model

A computational model of the field was developed in 1994 for the Bay of Plenty Regional Council and is described fully in the report by *Burnell and Young (1994)*. The 1994 model incorporated many of the elements of the conceptual model and generally provided a satisfactory fit to the field data. Acceptable matches were obtained to heat flow changes at Whakarewarewa and water level changes in most of the geothermal monitor wells. For example, the model match to the monitor well data M1 that was available in 1994 is shown in Figure 8. However, the model match to monitor well data from M6 and M9 was not very good. For example, Figure 9 shows the model match for M6 to the data available in 1994.

The 1994 model did acceptably match the response of heat flow at Whakarewarewa and mass flow at Kuirau Park as a result of changes in withdrawal from the field. This match was satisfactory for the tasks required at the time. These tasks involved testing the effects of a number of withdrawal scenarios on the outflows in the field. But it is now appropriate to review that model in light of improvements in the state-of-the-art in geothermal modelling.

The purpose of this work is to review and update the 1994 model to:
1. Ensure it conforms with current state-of-the-art geothermal modelling practices;
2. Improve the match of the computational model to the conceptual model;
3. Check the match of model predictions to historical and recent data and improve the match if possible;

The first task that was undertaken was to check the match of the 1994 model against recent data. Since the 1994 model was developed, the pattern of usage in the field has changed and water levels have continued to rise in some wells. Updated production and reinjection rates were added to the 1994 model and the model was run out to 2005. Once again, the match of the model was satisfactory for some of the monitor wells as shown in Figure 10, but the model did not match some

of the recent changes seen in other wells – for instance recent water level changes as shown in Figure 11. As a result of the quality of the match of the model and the stated aims of the work it was decided there was a strong need to modify the 1994 model in order to improve the representation of the conceptual model and the match to the monitoring data.
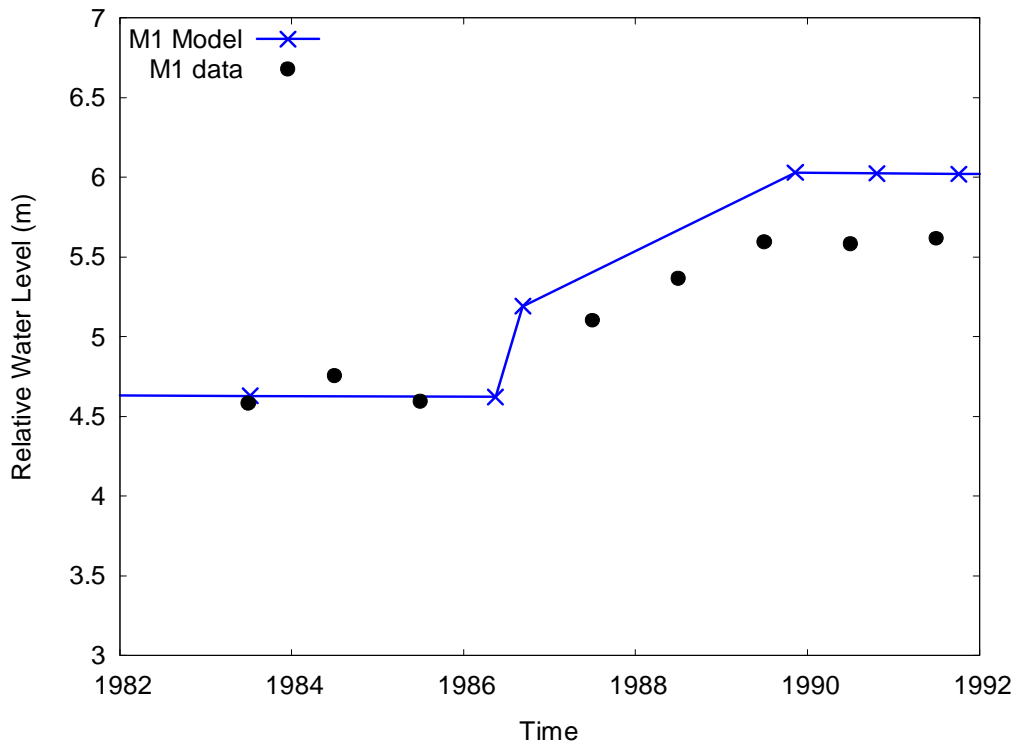
Figure 8: Match of the 1994 model to the relative water level in monitor well M1 available in 1994
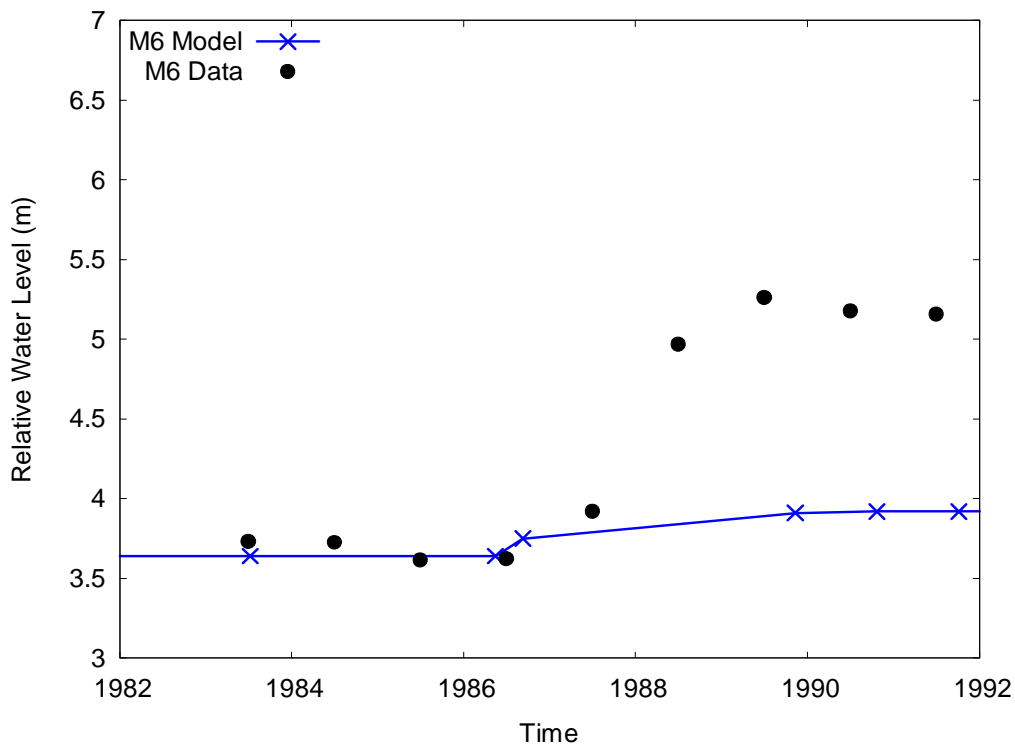
Figure 9: Match of 1994 model to the relative water level in monitor well M6 available in 1994
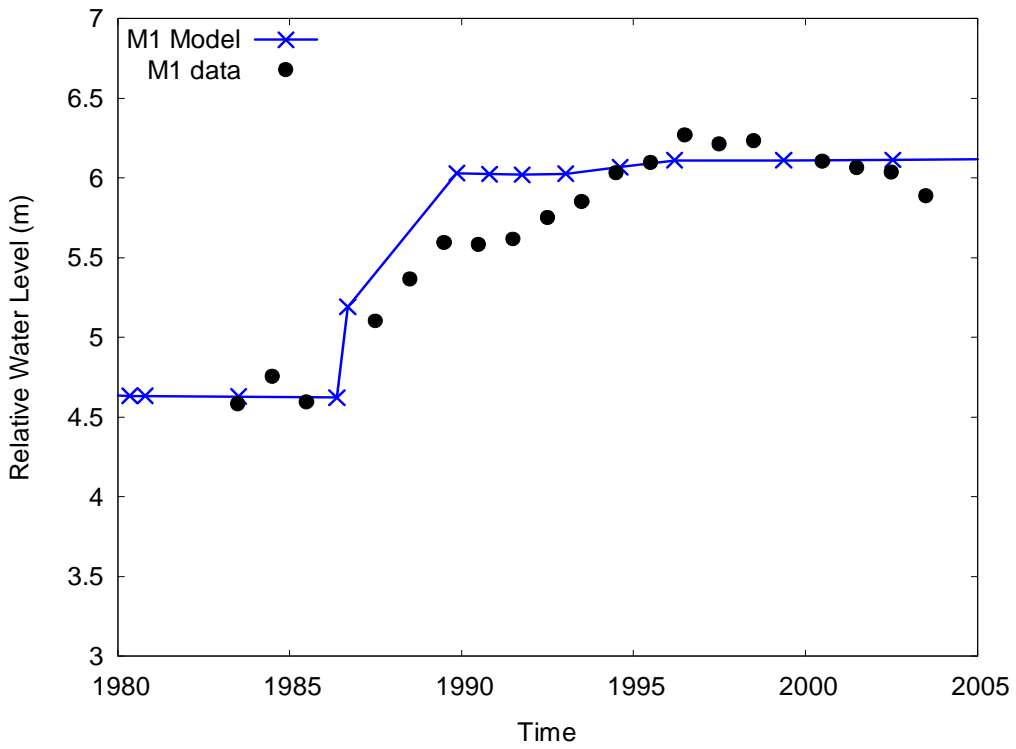
Figure 10: Match of 1994 model to the relative water level in monitor well M1 including new data up to 2003.
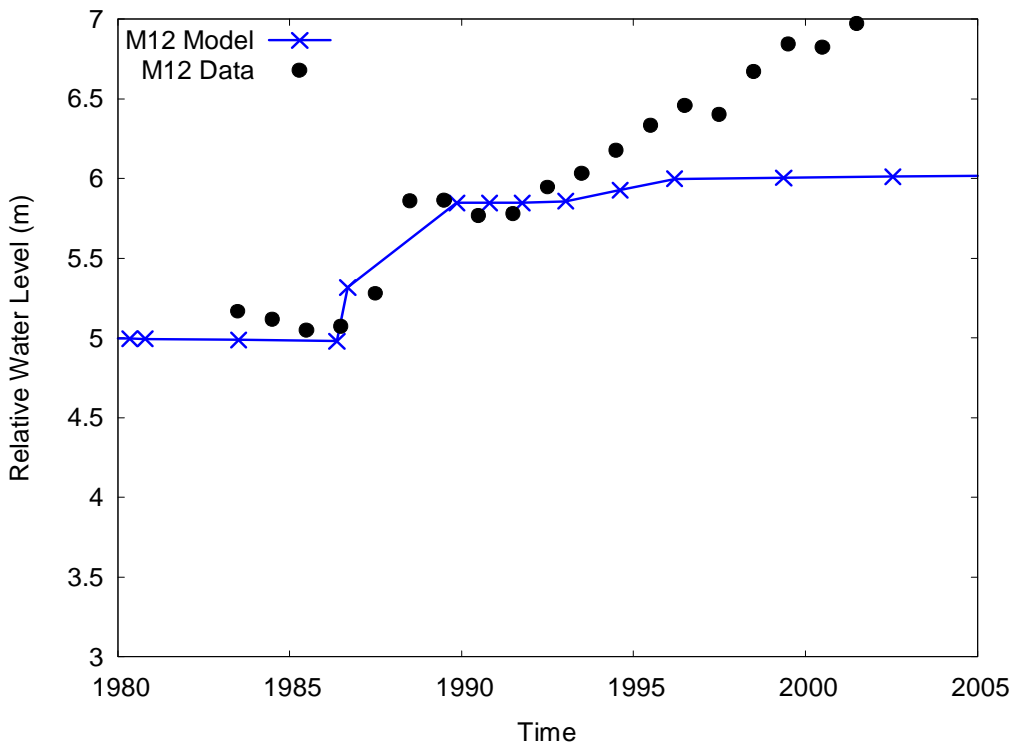
Figure 11: Match of 1994 model to the relative water level in monitor well M12 including new data up to 2003.

6   Overview of the Computational Model

The computational model of the Rotorua geothermal field is constructed by preparing inputs for a geothermal simulator called TOUGH2. TOUGH2 is a computer program originally developed at Lawrence Berkeley National Laboratory (*Pruess (1991)*). The simulator is able to calculate the pressures, temperatures, chloride concentrations and flows in a geothermal system.

The input required by the simulator describes the geology, inflows and outflows. This information is given in terms of:
* A 3-D computational grid covering the system;
* The specification of rock properties in each element, including permeability, porosity, specific heat and conductivity;
* Pressures, temperatures and chloride concentrations prescribed around the boundaries of the system;
* Any inflows and outflows that occur in the system;
* Injections and withdrawals that are imposed on the system.

The model described here is an updated version of the 1994 model. Full details of the model structure can be found in Section 12 in the Appendix.

The 1994 model was firstly altered to improve the representation of the conceptual model. For example:
* The extent of the Rotorua Rhyolite was changed to follow the contours shown in Figure 4 more closely.
* A layer of sediments were placed over the ignimbrite in the Whakarewarewa region.
* The ICBF extends to a depth of 150 m below the surface.
* Overlying layers of groundwater and air are included in the model.
* Surface topography is included in the model with the south end of the model being 40m higher than the lake end.
* The horizontal extent of the model has been increased to include areas of cold groundwater surrounding the geothermal aquifer.
* Rainfall is now included in the model.

Other improvements were also made to the 1994 model:
* The number of grid blocks used in the model was increased. The 1994 model had 462 blocks and the 2004 model has 3,550 blocks.
* The treatment of boundary conditions has been greatly improved. The model now no longer relies on pressures along the east and west boundaries.

The model grid and representation of the geology is shown in Figure 12 to Figure 18. The model is constructed of 7 horizontal layers between –250 and 320 m.a.s.l. A grid of blocks and geological structures are prescribed on each layer. Different geological structures are represented in the model by assigning different material properties to model grid blocks. Features such as the rhyolite domes are represented by increasing the extent of the rhyolite regions with depth. The locations of the model regions are designed to approximate the positions of the geological formations and are shown in Figure 14 to Figure 18. The material properties that correspond to the regions shown in these figures are given in Section 12.2.
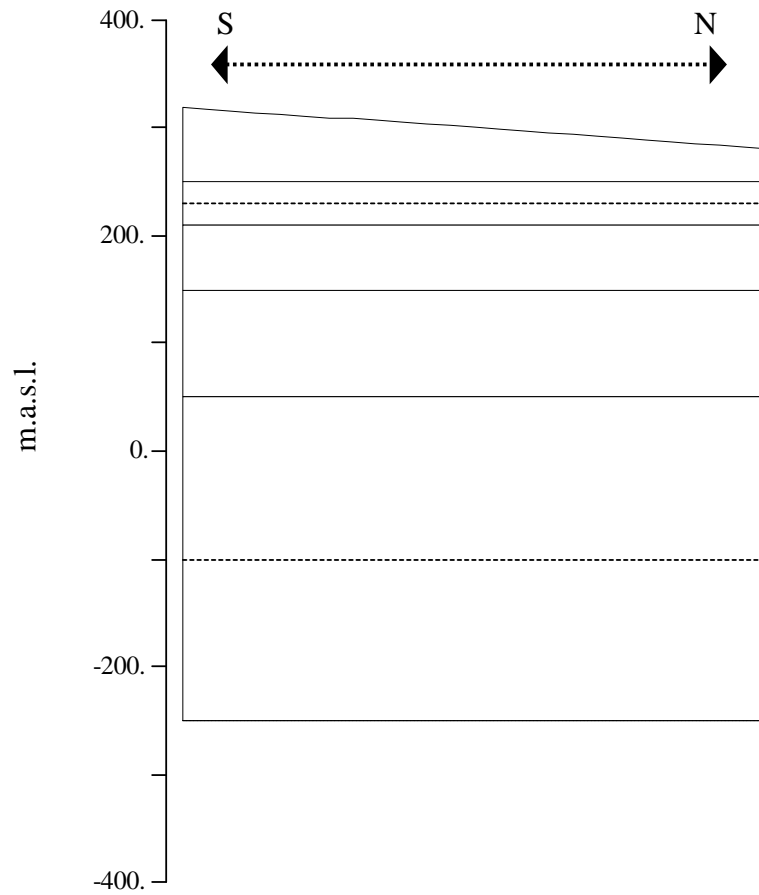
Figure 12: Vertical structure of the layers that make up the model. The vertical scale is m.a.s.l. The lines show layer boundaries in the model, and the dashed lines indicate that the layer has been split into two identical layers. The sloped surface in the upper layer is highest in the south and lowest in the north at the lake end of the model. The geological structure is prescribed on each layer and shown in the following figures.
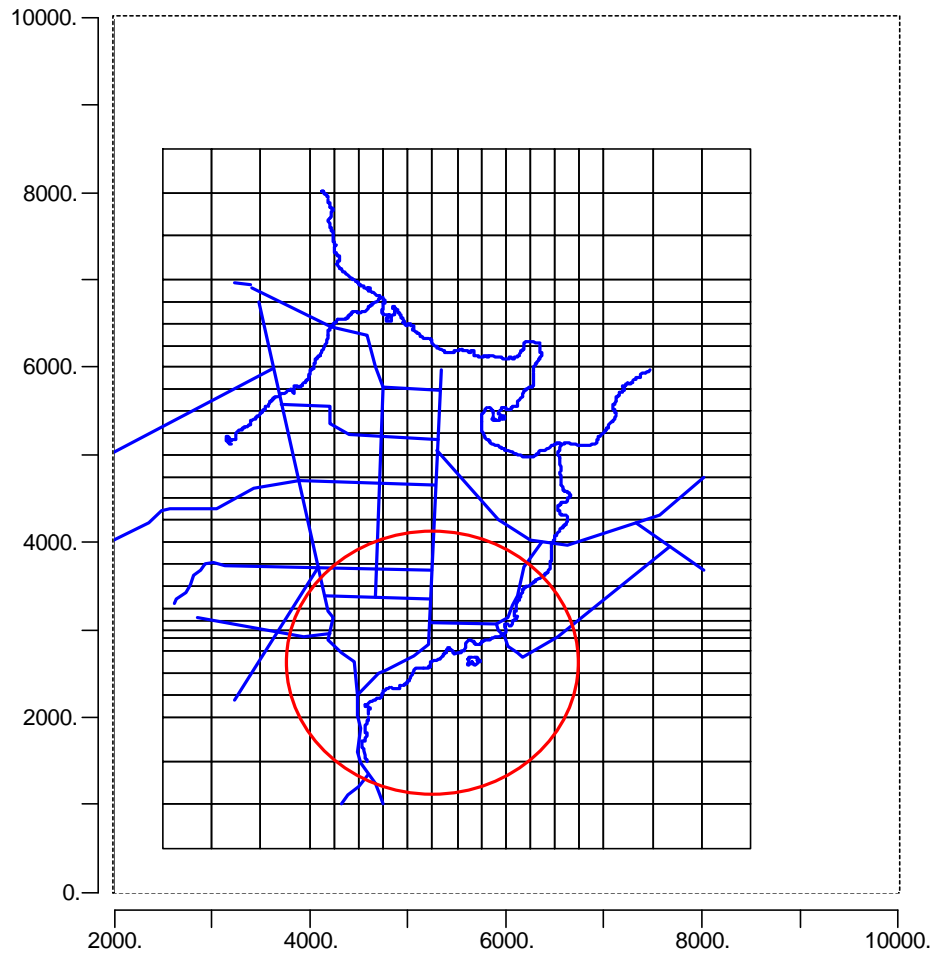
Figure 13: Grid layout in a horizontal layer. The coordinates refer to map coordinates with (2,000, 0) on the diagram corresponding to (2790,000N, 6332,000E) in map coordinates. The blue lines are local roads, streams and the lakefront, and the red line approximately shows the 1.5km exclusion zone.
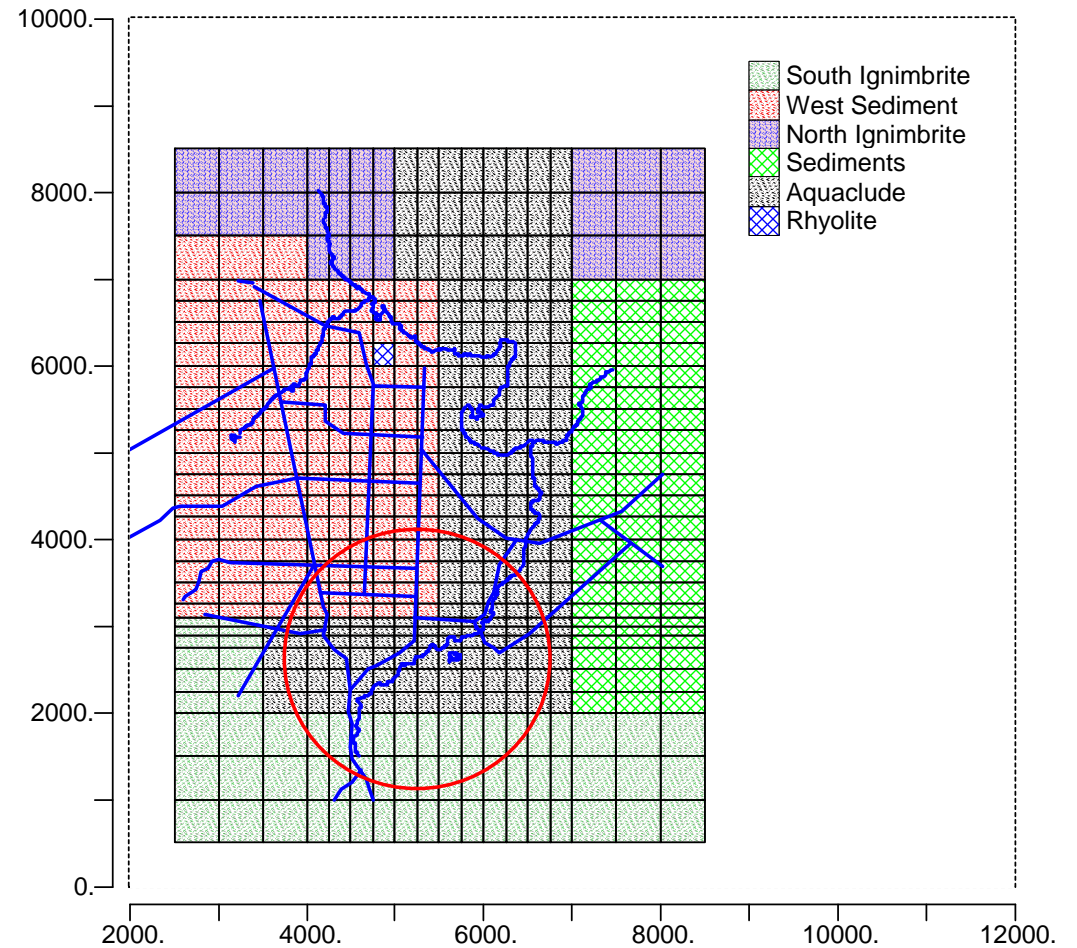
Figure 14: Materials used in the upper layer of the model between 250 and 320 m.a.s.l.
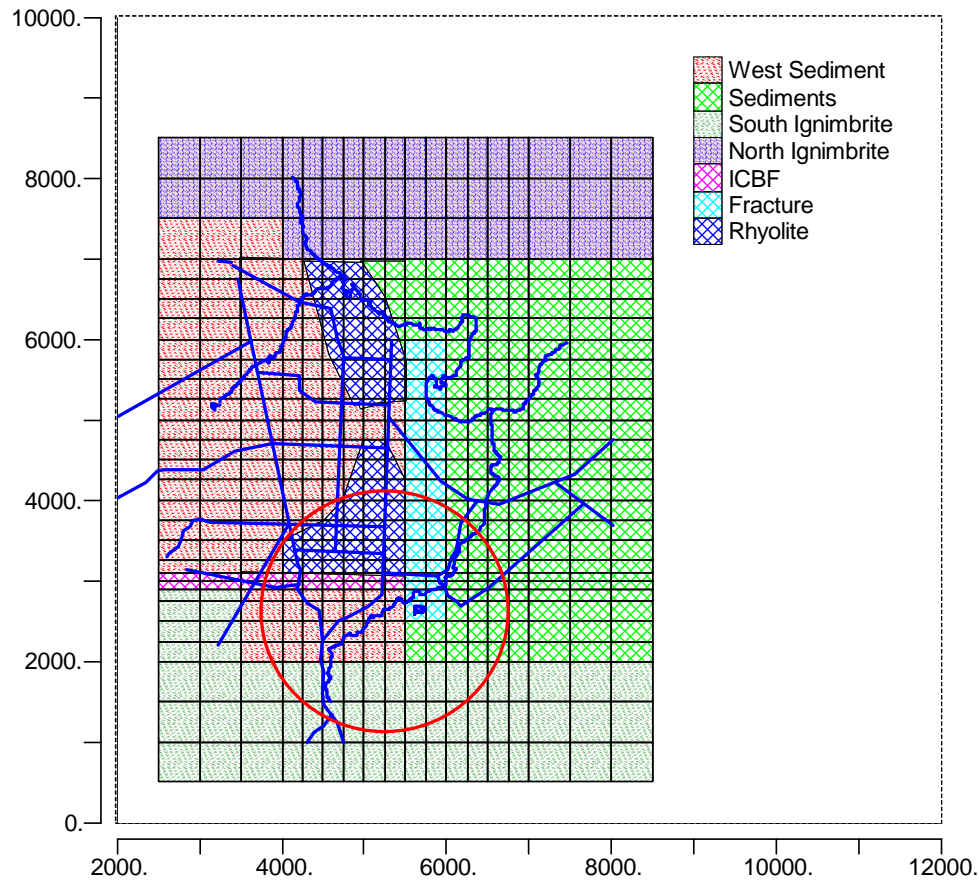
Figure 15: Materials used in the model layers between 210 and 230 m.a.s.l. and 230 and 250 m.a.s.l.
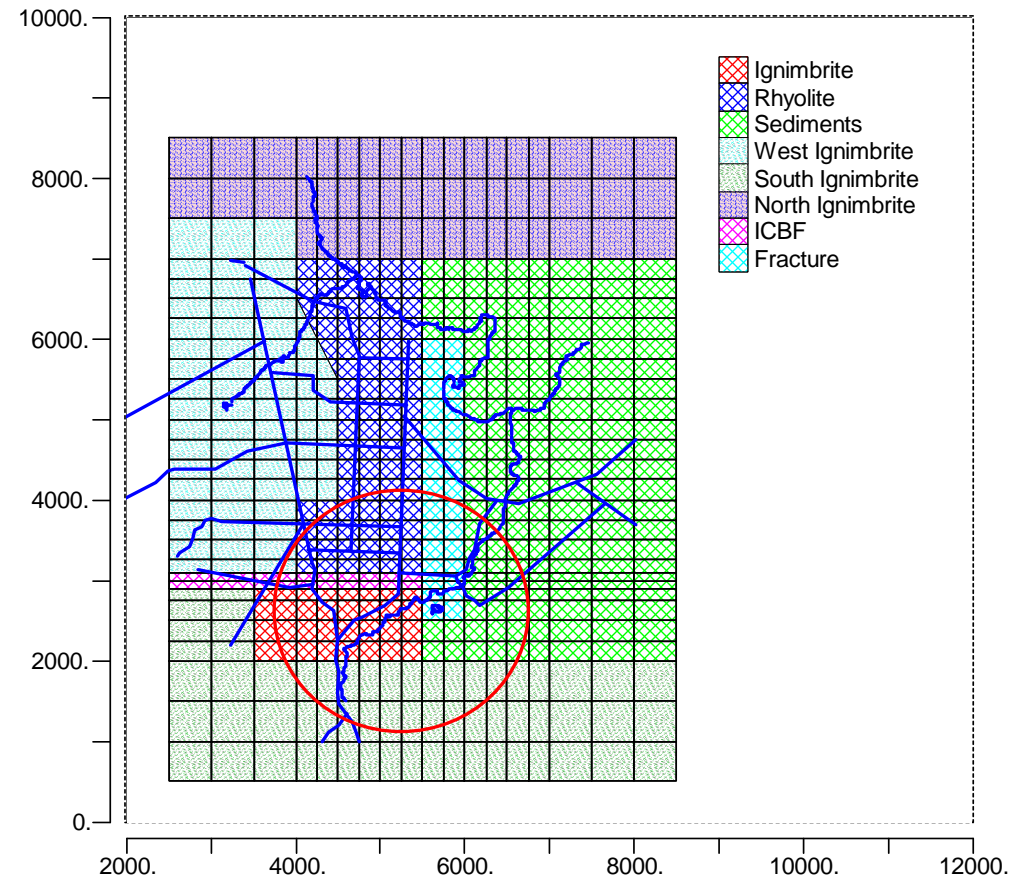
Figure 16: Materials used in the model layer between 150 and 210 m.a.s.l.
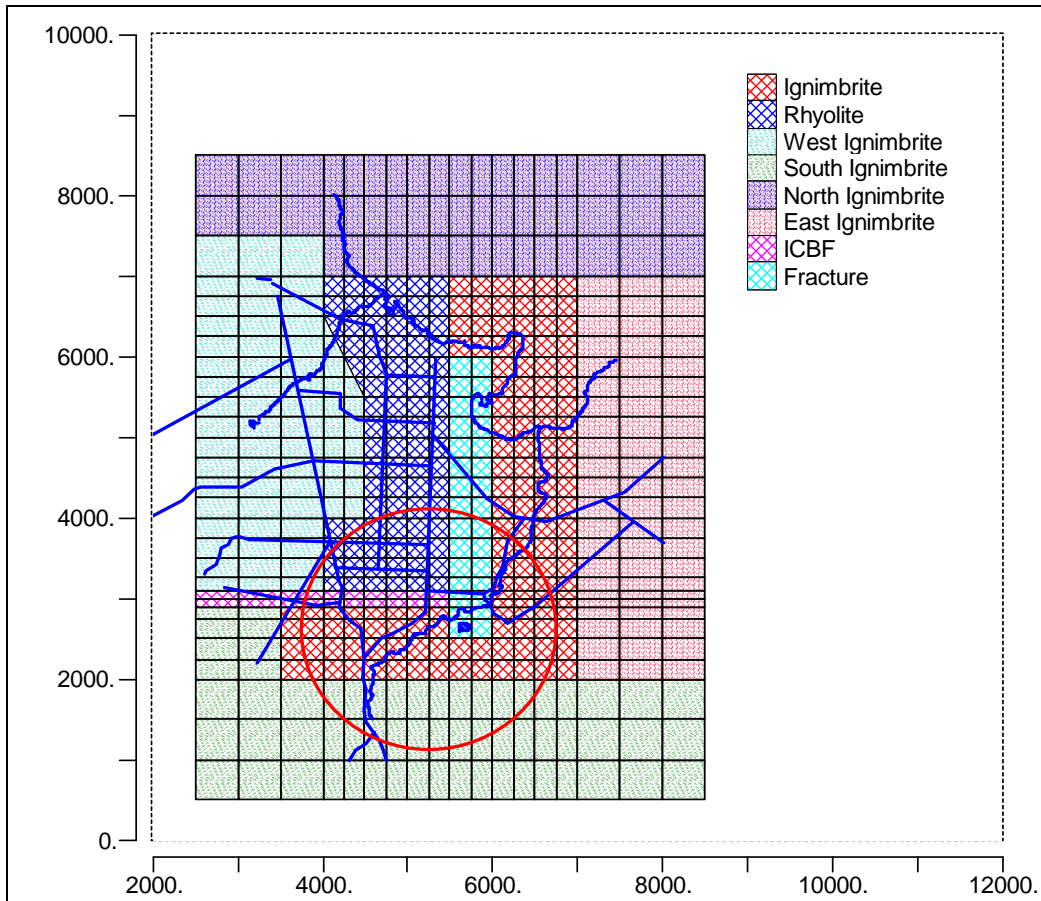
Figure 17: Materials used in the model layer between 50 and 150 m.a.s.l.
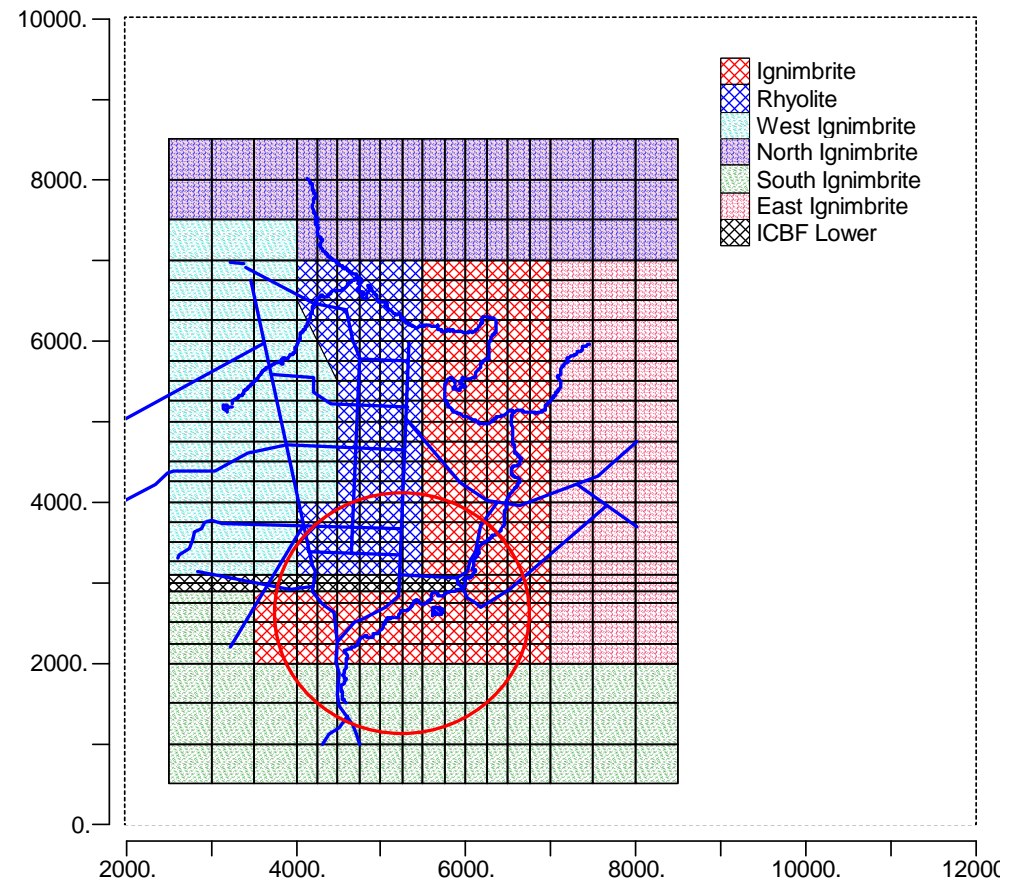
Figure 18: Materials used in the model layers between –250 and –100 m.a.s.l. and –100 and 50 m.a.s.l.

7   Model Results

The values of the model parameters were adjusted until the model results gave a satisfactory fit to monitoring data collected prior to 1992. 1992 was chosen as the greatest changes had taken place in the field by then. Many iterations of this process were required until a satisfactory set of parameters was obtained. The data used in this process was:

- Inferred heat flows and pressures from the natural state;
- Heat flows, pressures and temperatures from 1985;
- Heat and mass flows after in 1990
- Water level changes in monitor wells from 1986 to 1992.

7.1   The Natural State

The natural state represents the state of the field before production began. In order to simulate the effects of production on the field, it is necessary to start the model from an unchanging state. This unchanging state should correspond to the natural state. There is little field data about the natural state with which to compare the model results. However, a number of researchers have made estimates of some of the conditions in the natural state. This information is presented in Section 11 of the Appendix. The aim was to ensure that the model results were at least consistent with the inferred conditions. The model temperatures and pressures in the natural state are shown in Figure 19 and Figure 20.
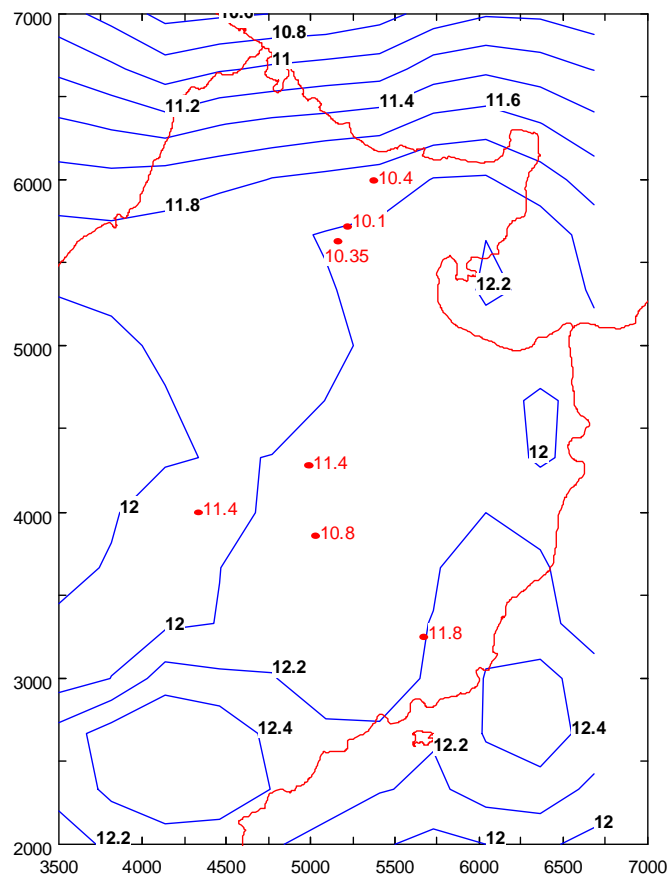
Figure 19: Model pressures in the natural state at 180 m.a.s.l. compared to measured pressures
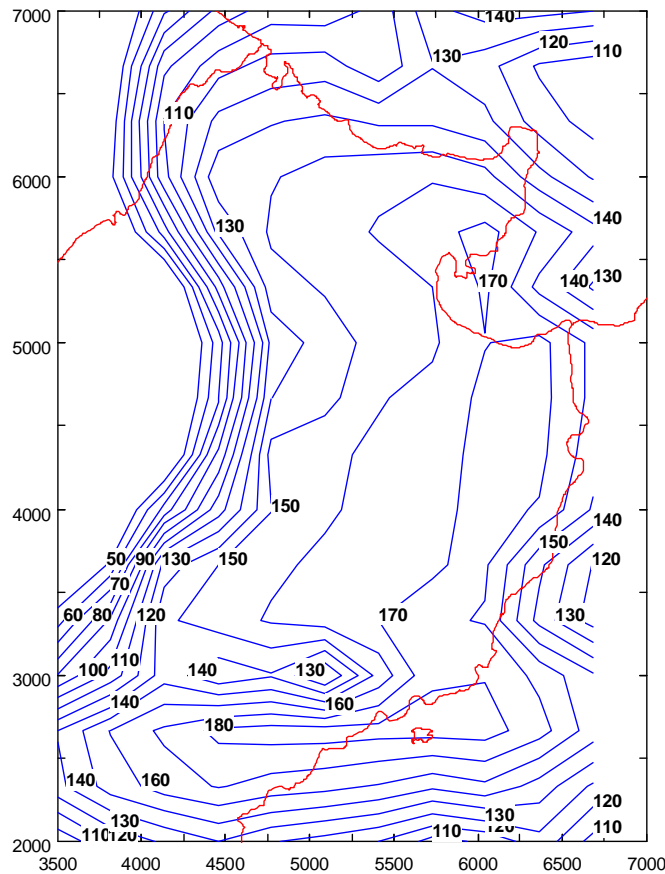
Figure 20: Model temperatures in the natural state at 180 m.a.s.l.

7.1.1   Summary of the Match of the Model to the Natural State

Surface Flows   The model heat flow from Whakarewarewa is 260 MW, compared with an inferred value of 300 MW. The model mass flow from Kuirau Park is 3,020 tonnes/day, and at Ngapuna/Puarenga Stream it is 9,670 tonnes/day, there are no corresponding measurements in these locations.

Pressure   The pressures shown in Figure 19 are higher than the measured values but show a similar pattern to the inferred data with higher pressures in the south and east and lower pressures at the lake end.

Temperatures   There is little data to compare the natural state temperatures with, but the results are consistent with the temperatures seen in 1985.

7.2   Match of the Pre-Closure State

The model was run for 30 years using the withdrawal pattern shown in Figure 21, and model results and measured data are shown in Figure 22 and Figure 28. This state is comparable to conditions in 1985, when the most data is available with which to compare the model results. The data is presented in Section 11 of the Appendix.

Surface Flows   The model heat flow from Whakarewarewa is 177 MW compared to the measured flow of around 158 MW. There is no flow from Kuirau Park, and

63MW at Puarenga Stream/Ngapuna. This is consistent with observations that the Kuirau Park Lake essentially ceased overflowing, and Glover's observation of 70MW flow into Puarenga Stream north of FRI in 1990.

Pressures The model pressures at 180 m.a.s.l. shown in Figure 22 are too high. However, they do show similar spatial behaviour to the measured pressures shown in Figure 23, with a pressure high in the southeast, rapidly changing near the ICBF and a pressure low in the north. Further, the changes in pressure since production started are of the right magnitude with declines of about 0.2 bar.

Temperatures The temperature contours in Figure 24 compare well with contours of the measured temperatures shown in Figure 25. Also boiling regions at 220 m.a.s.l. are shown in Figure 26. These approximately agree with the boiling zones inferred from well data.
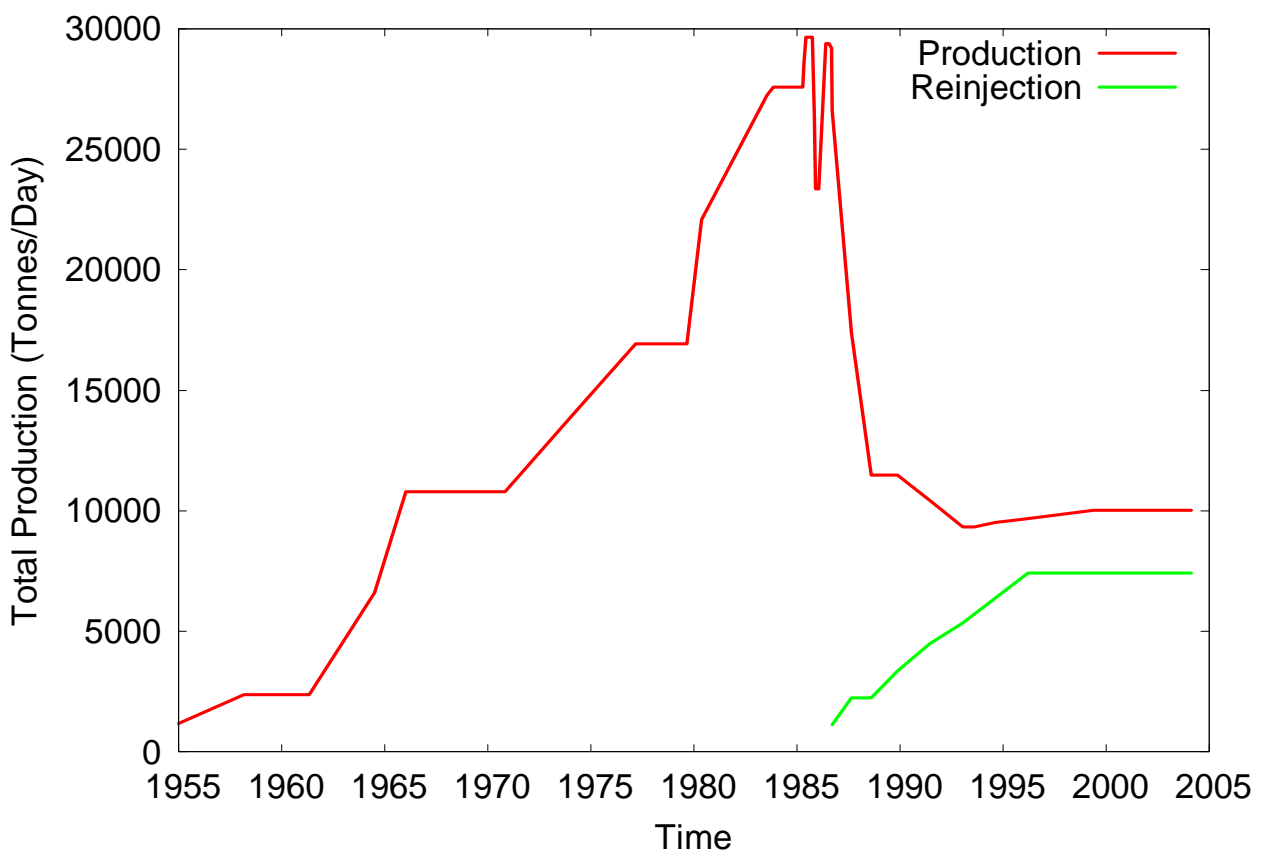
Figure 21: Production rates used in the model
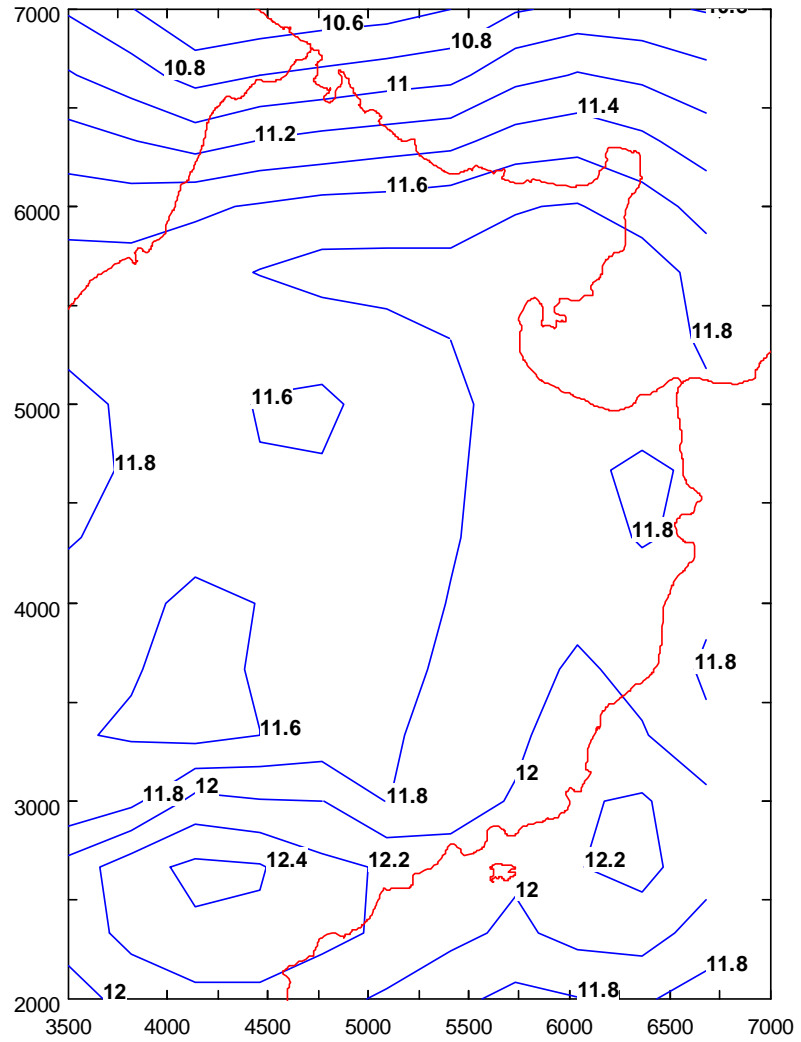
Figure 22: Model pressures at 180 m.a.s.l. in 1985
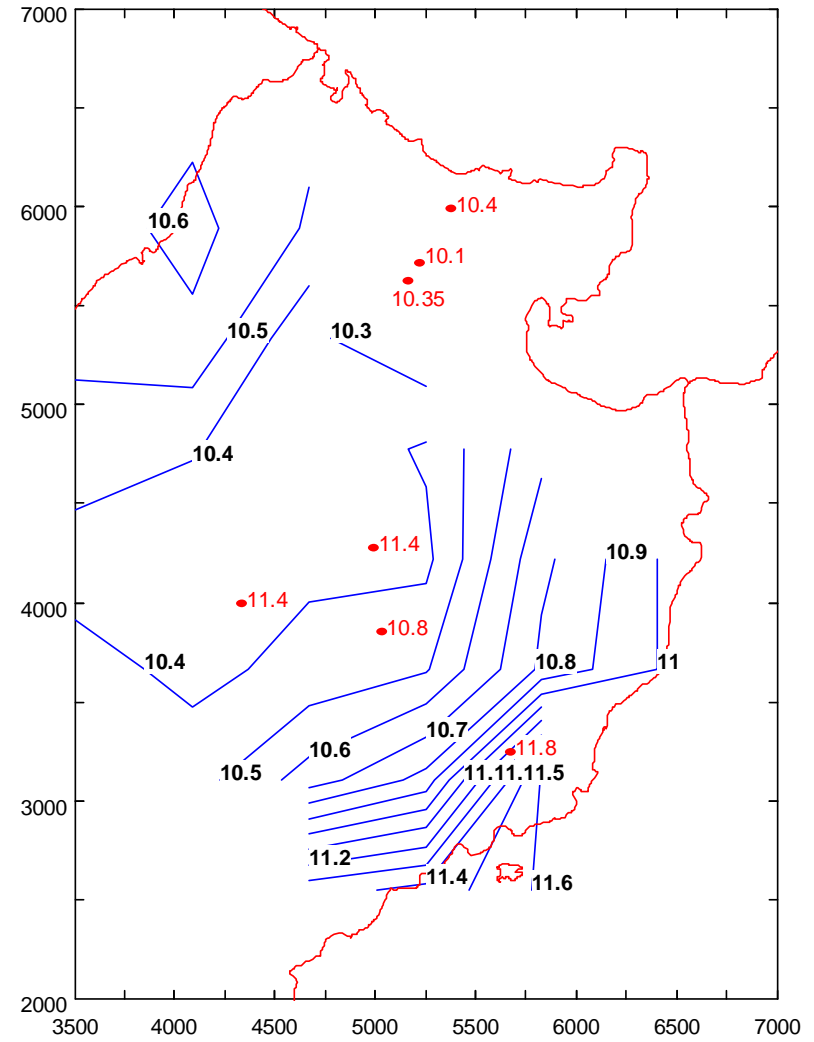
Figure 23: Calculated pressures (bars) at 180 m.a.s.l. after *Grant et al (1985)*. The red numbers are pressures from before 1960, and the blue contours are from 1985
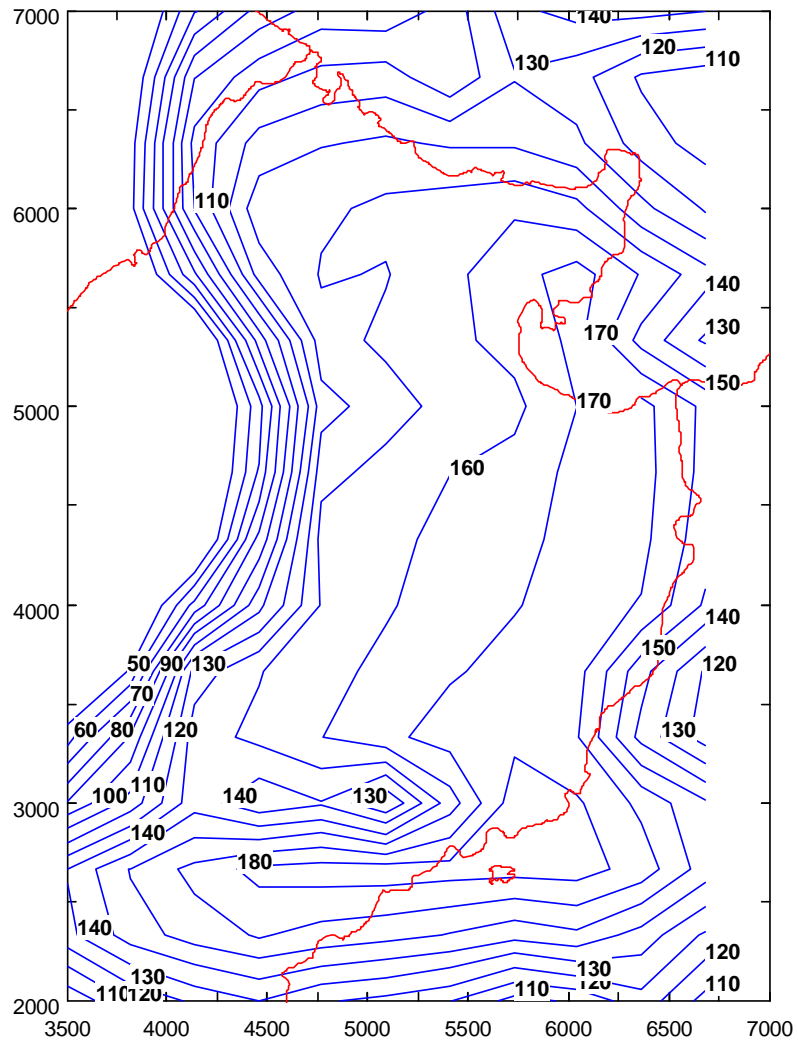
Figure 24: Model temperatures at 180 m.a.s.l. in 1985
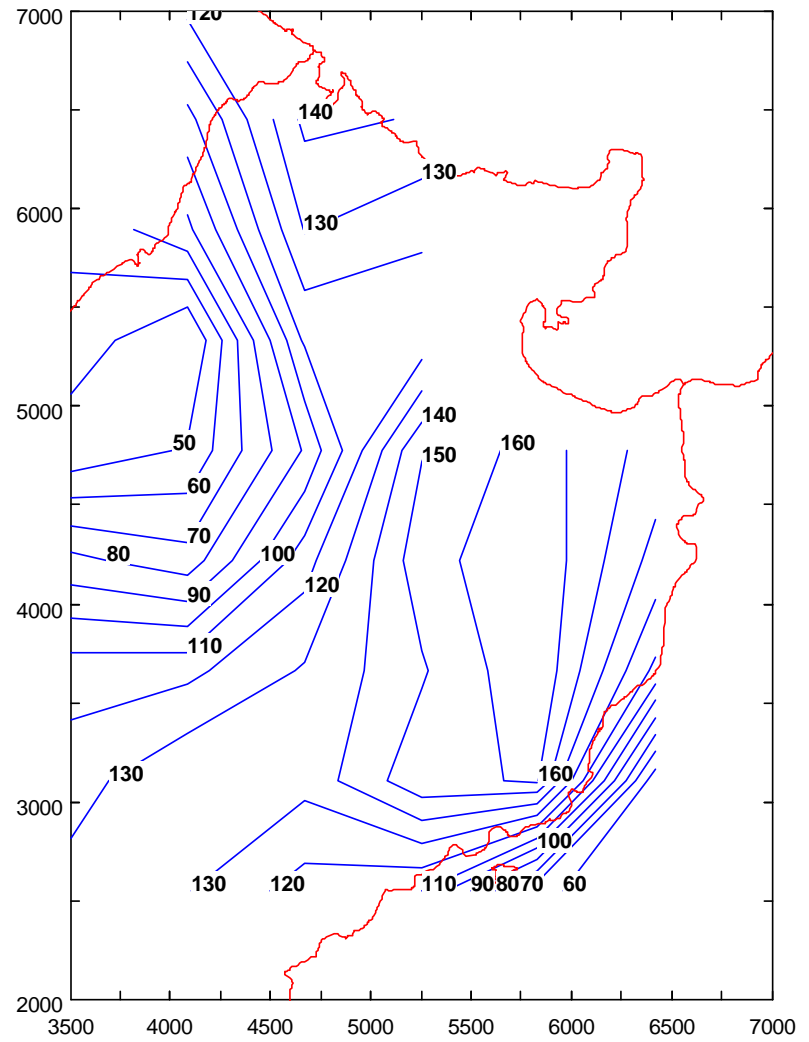
Figure 25: Contours of measured temperatures at 180 m.a.s.l. in 1985 after Wood
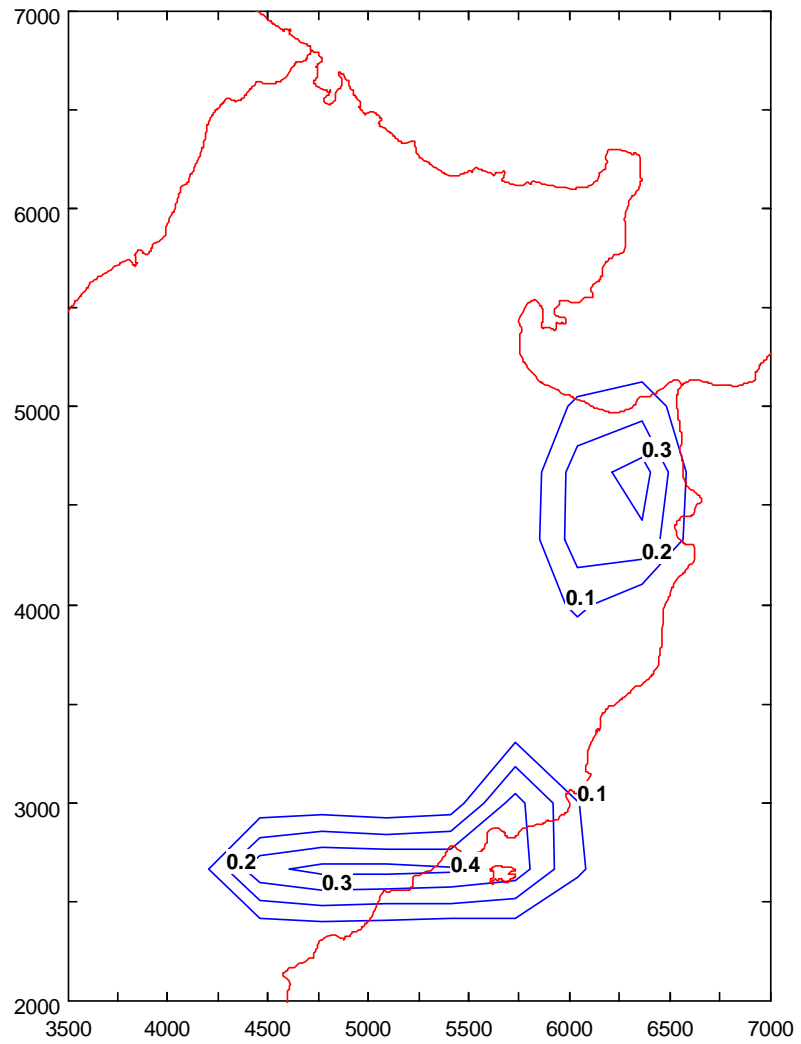
Figure 26: Model steam saturations at 220 m.a.s.l. in 1985
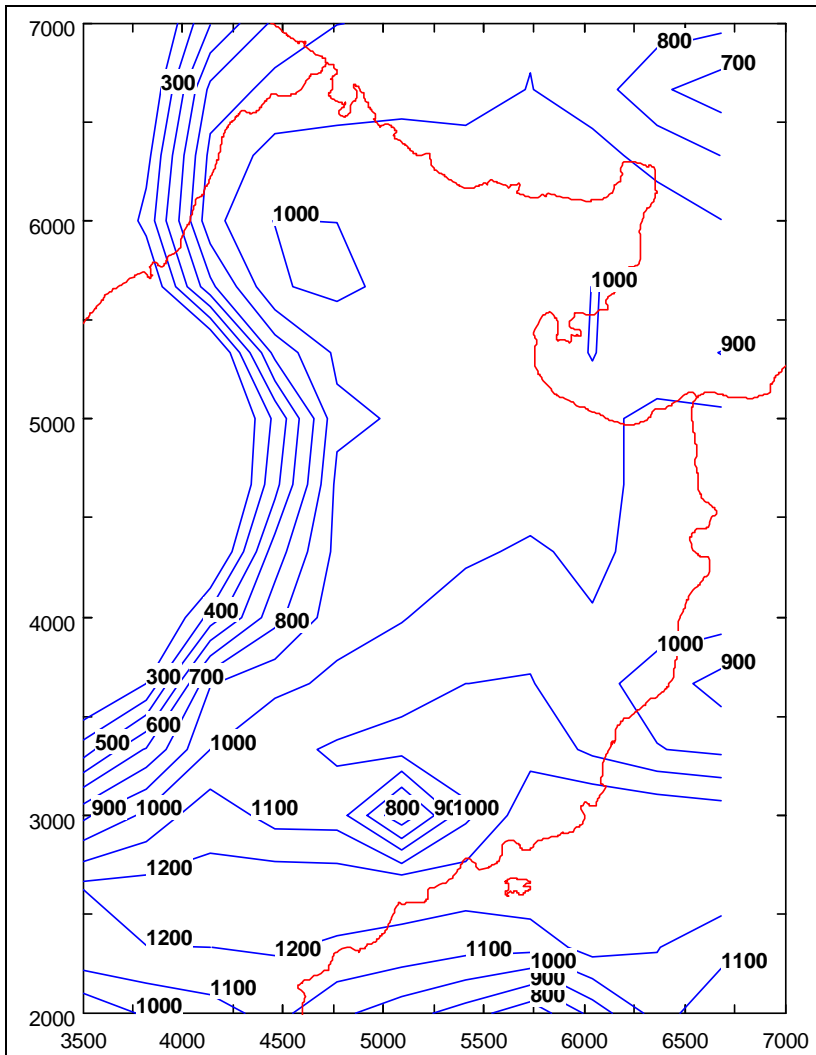
Figure 27: Model chloride concentrations at 180 m.a.s.l. in 1989
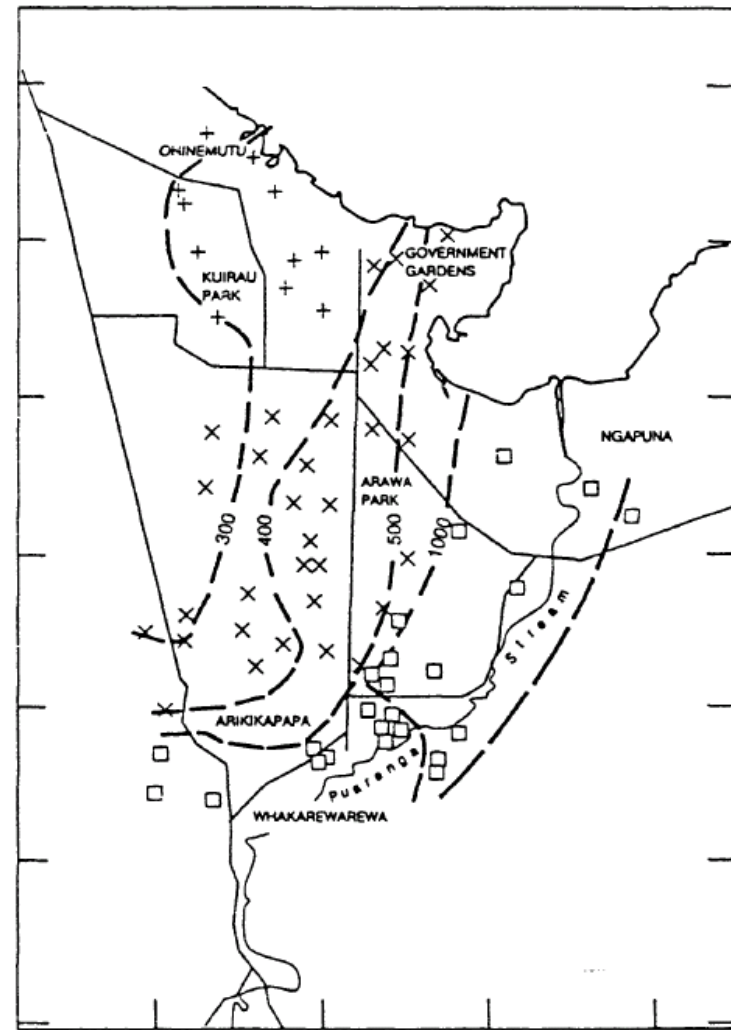
Figure 28: Chloride concentrations from 1989 in ppm from Stewart et al (1992)

7.3 Response to the 1986 Bore Closure Programme

The model response to the 1986 Bore Closure Programme in 5 monitor wells is shown in Figure 29 through to Figure 33. The locations of the monitor wells is shown in Figure 42.

Surface Flows   The model heat flow from Whakarewarewa is 245 MW in 1993 which compares well with the estimate of more than 229 MW in 2000. The modelled mass flow from Kuirau Park of 1,380 tonnes/day is a good match to the observation that the lake was flowing at a rate of 3,456 tonnes/day in 1993 which corresponds to a flow of hot geothermal fluid of about 1,728 tonnes/day. In the Purenga Stream area, there is a heat flow of 74 MW in 1993 which is a good match to the figure of 77±20 MW reported by *Glover (1992)* from 1990.

Pressures   Pressure changes in the model are compared to water level changes in the monitor wells in Figure 29 through Figure 33. The modelled recovery gives good agreement except for M12. A comparison of model results and measurements in 1990 is given in the following table:

Well	Change between 1986–1990		Change between 1990–2000	
	Measured (m)	*Modelled (m)*	*Measured (m)*	*Modelled (m)*
M1	1.1	1.1	0.5	0.4
M6	1.6	1.6	0.4	0.3
M9	2.3	1.7	> 0.4	0.7
M12	0.9	0.7	1.0	0.1
M16	1.9	1.9	0.5	0.4

Temperatures   There is little temperature data in 1993 with which to compare the results.
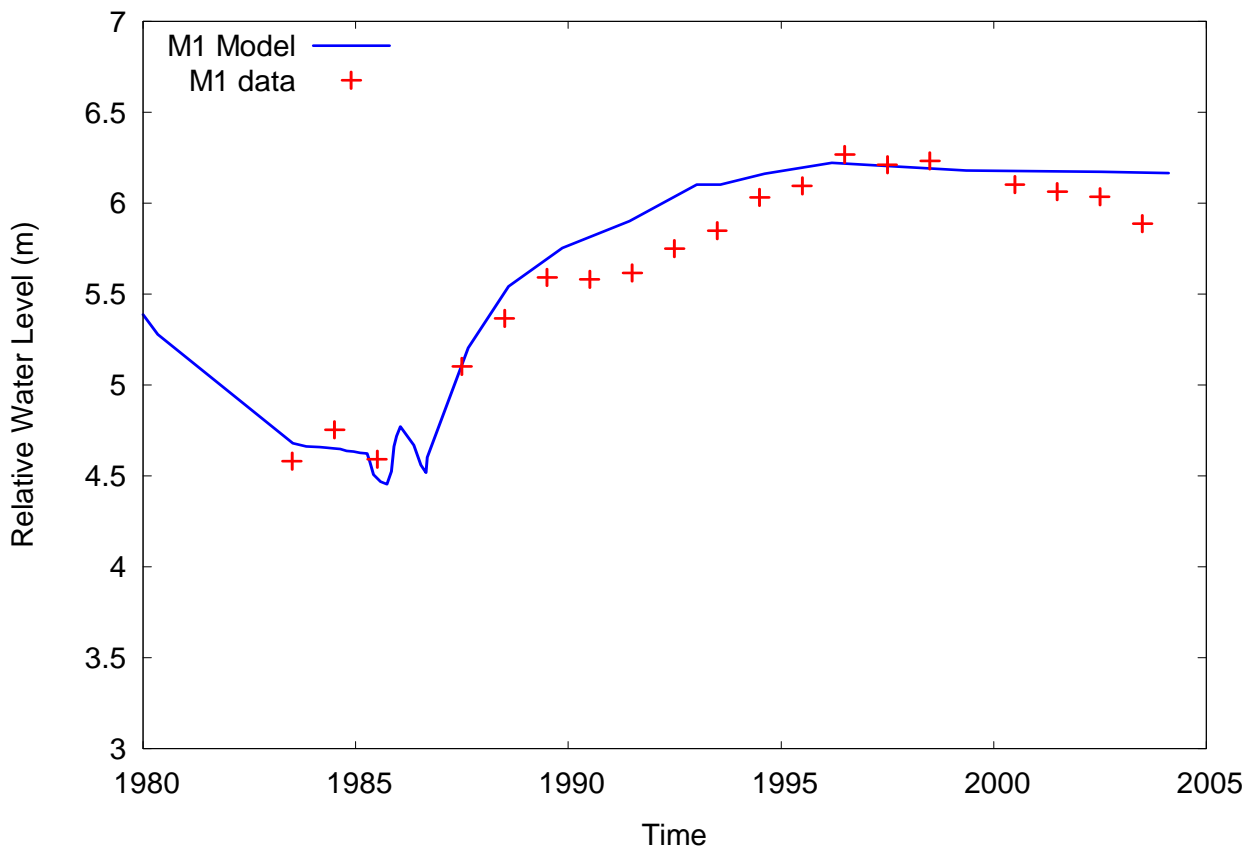
Figure 29: Model water levels at M1
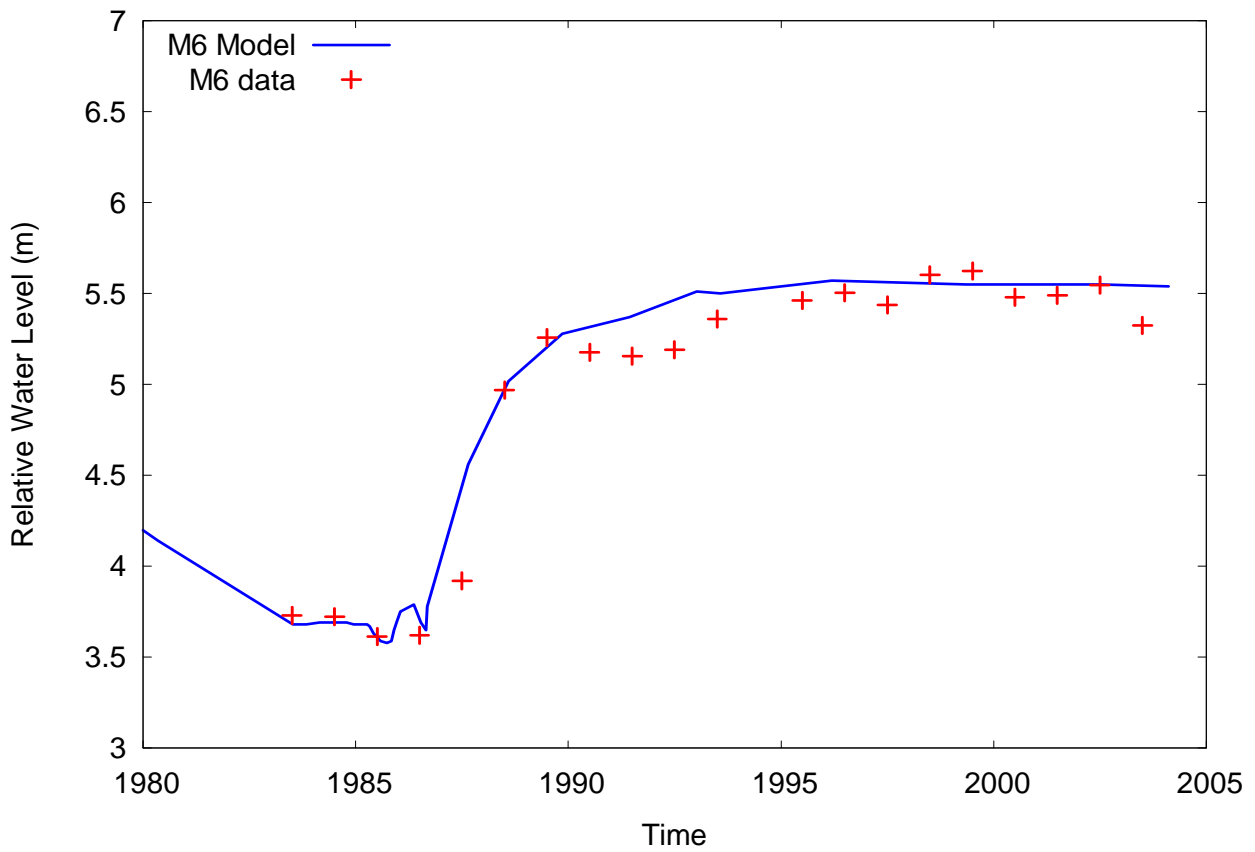
Figure 30: Model water levels at M6
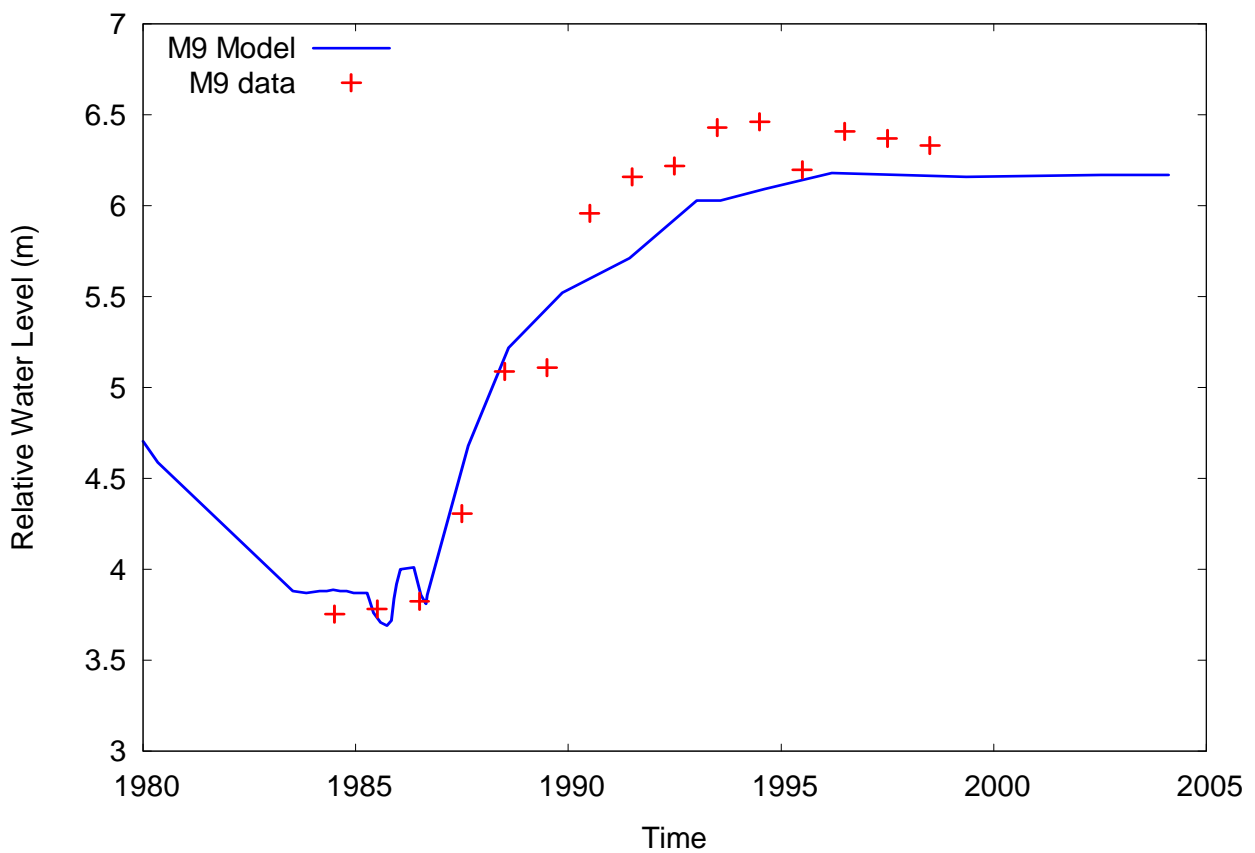
Figure 31: Model water levels at M9
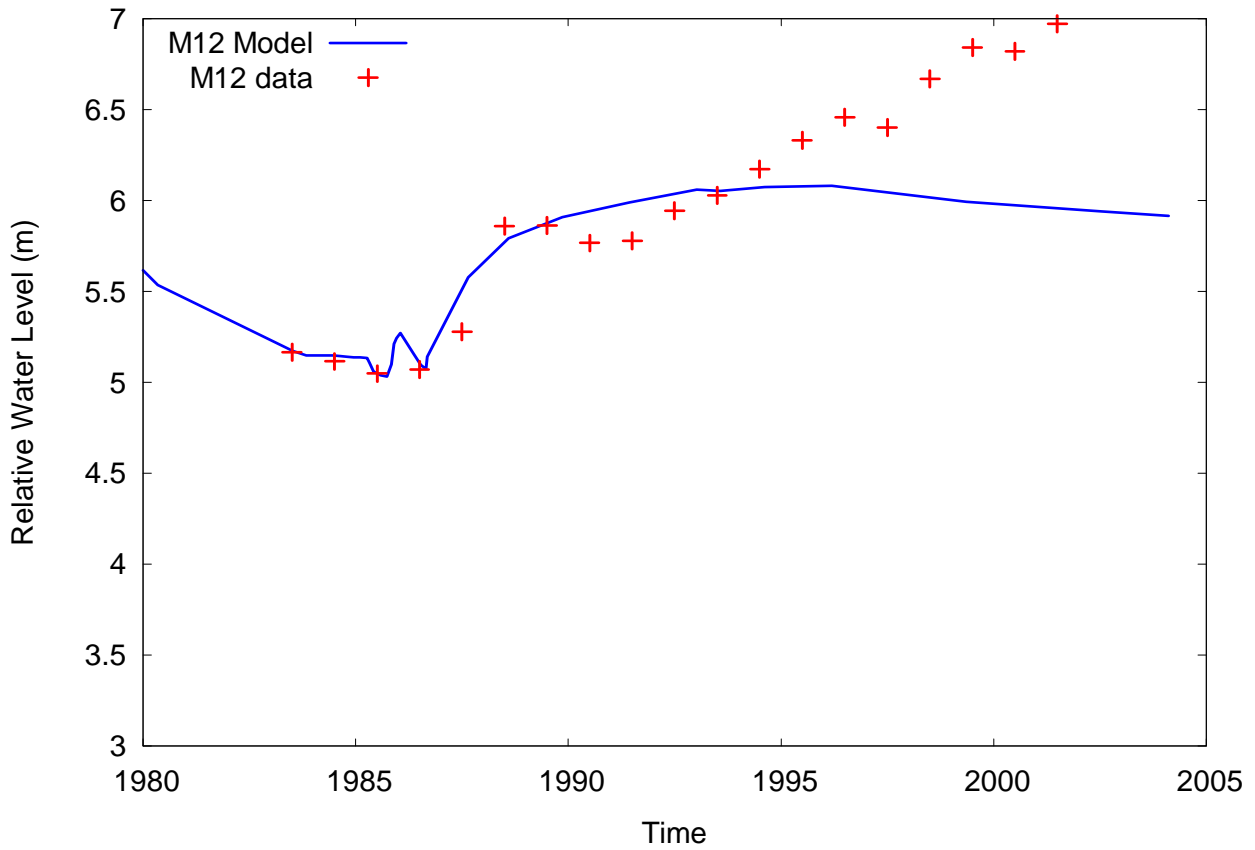
Figure 32: Model water levels at M12
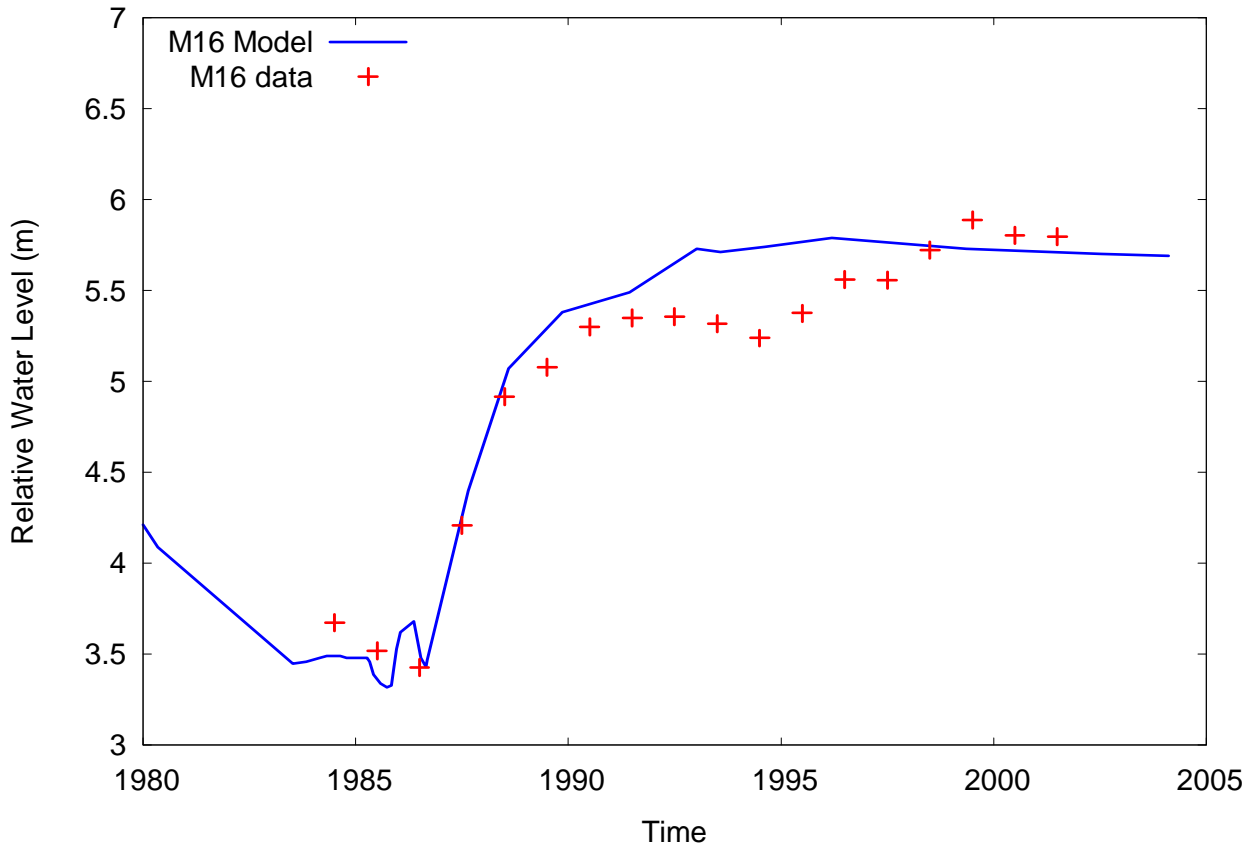
Figure 33: Model water levels at M16

7.4   Seasonal Variation in Production

Prior to the Bore Closure Programme, water levels at Rotorua showed a seasonal variation. This can be seen in Figure 34, which shows the response of M16 to the changes in production. During the summer period production reduced by approximately 6,000 tonnes/day, and water levels increased over that period. During the winter months, production increased and water levels decreased. This behaviour was investigated in the model by reducing production over the summer of 1985/6 by 6,000 tonnes/day as seen in the production rates of Figure 21. The water level at the monitor wells was then compared with measured values.

Table 1: Response to seasonal change in production between winter and summer 1985

Well	Measured Response (m)	Modelled Response (m)
M6	0.6-0.8	0.2
M9	0.5	0.3
M12	0.6	0.25
M16	0.3	0.3

The model underestimates most of the responses. Possibly the reason for this is that the model does not contain enough local detail in the withdrawal rates, to estimate these changes. Lack of detail in the withdrawal rates, means that pressure changes will be averaged out over larger regions.
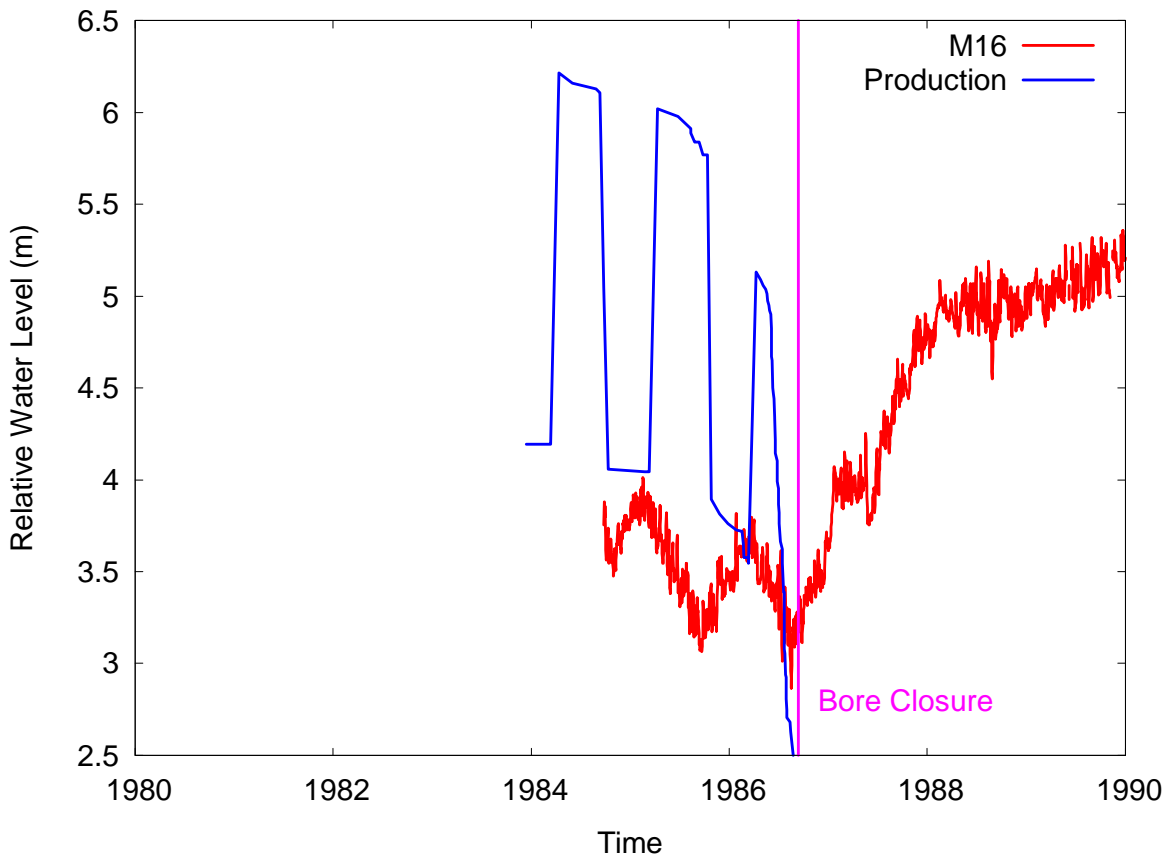
Figure 34: Comparison of water level response from M16 to seasonal production rates.

7.5 Match to Post Closure Monitor Well Measurements to 2004

As discussed in Section 11.7, the increases seen in the monitor wells M12 and M16 from 1995 cannot yet be explained. Without any significant increase in the net withdrawal over that period, the model does not predict these observed changes as seen in Figure 32.

The continued increase of the water level at M12 is of concern, since the controlling mechanism is not understood. Some possibilities are:

- A seismic event may have opened a fracture under Pukeroa Dome allowing extra upflow to occur in that area.
- Changes in inflow due to climatic changes.
- Changes in production or reinjection around M12;
- Reinjection near M12 may be into a less permeable formation than the underlying rhyolite, and the travel time through that formation is of the order of years rather than days.

The third and fourth possibilities are less likely, since we understand that EBOP have undertaken a thorough audit of all production and reinjection. Further most of the reinjection wells that are used were previously operated as production wells. Consequently most of these wells will have feeds in permeable rock.

The first and second possibilities were tested by increasing the deep hot upflow under Pukeroa Dome in the model. This was done increasing the upflow by an extra 3,800 tonnes/day from 1996. When this was done the water level in M12 increased at about the right rate as seen in Figure 35. Also, M16 showed a response around 1996, which can also be seen in the data in Figure 36. This explanation for the increase in water levels is also consistent with:

- the increased thermal activity that is being seen around the Kuirau Park area and
- small increases in geothermometer temperatures and chloride concentrations - *Mroczek et al (2003)*
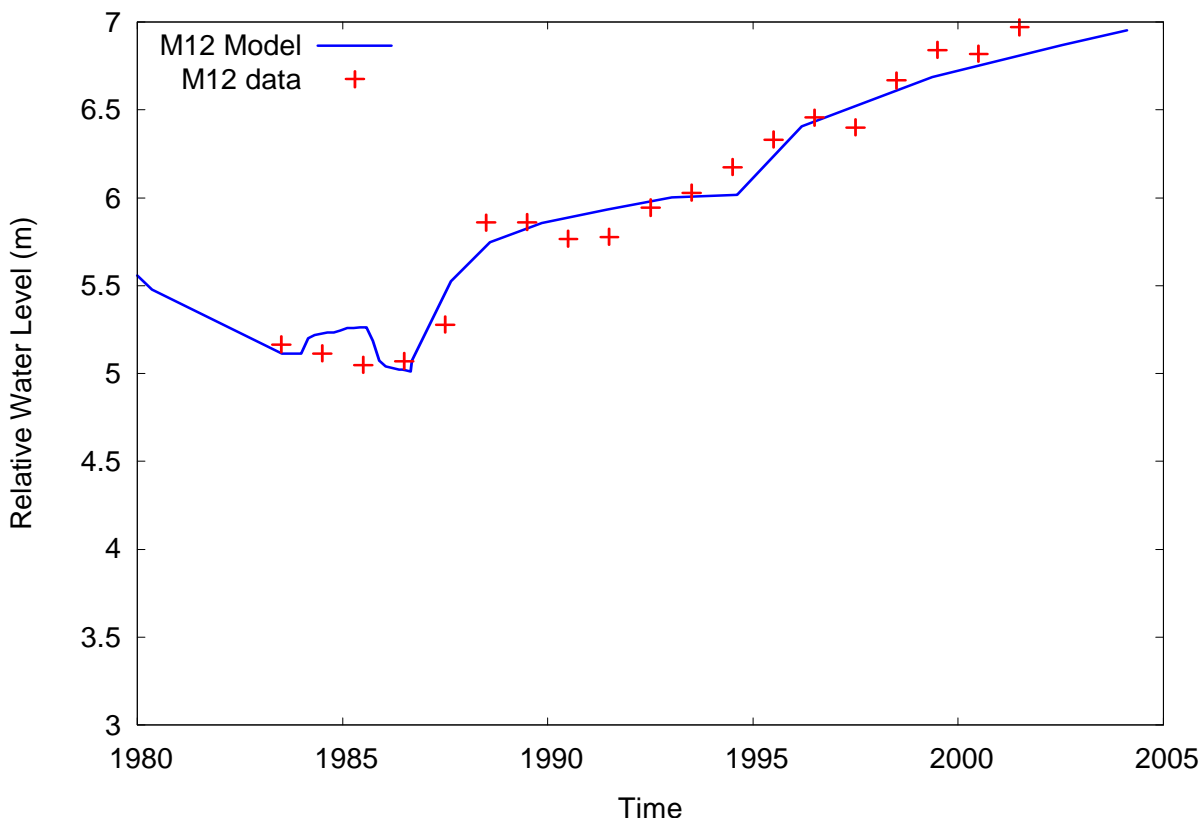
Figure 35: Model water levels at M12 if the hot upflow under Pukeroa Dome is increased by 3,800 tonnes/day in 1996.
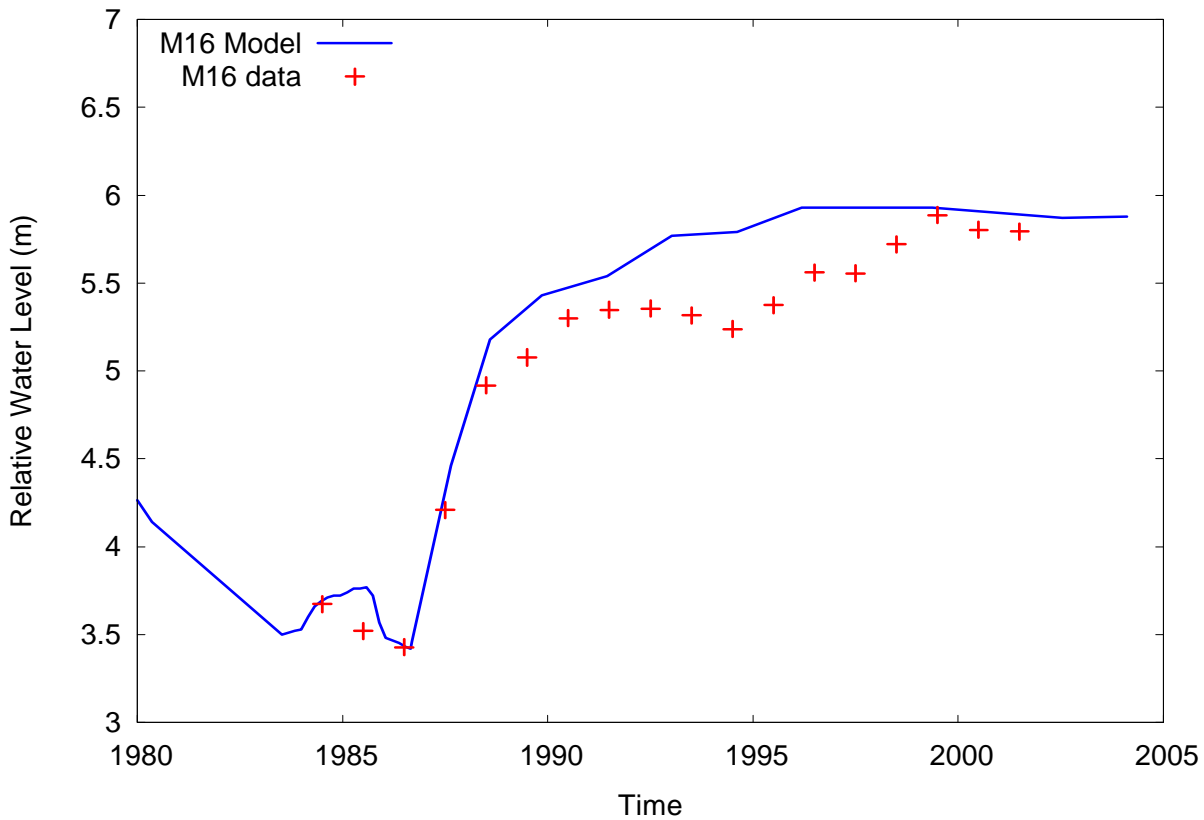
Figure 36: Model water levels at M16 if the hot upflow under Pukeroa Dome is increased by 3,800 tonnes/day in 1996.

7.6 Overall Match of the Model

The match of the model to the absolute values of the pressure could be better. However, changes that occurred in the pressures over time are modelled acceptably, with a good match to the Bore Closure Programme. It is these pressure changes that are important in driving the changes in flow from Whakarewarewa. Taking all the quantities discussed above into consideration, the match of this model to the data can be considered quite acceptable.

The match of the model is summarised in the following table.

Table 2: Match of model to measured data

	Measured	**2004 Model**
Heat Flow at Whakarewarewa in natural state (MW)	~300	260
Heat Flow at Whakarewarewa in 1985 (MW)	158	176
Heat Flow at Whakarewarewa in 2000 (MW)	> 216	245
Mass Flow at Kuirau Park in 1986 (tonnes/day)	0	0
Mass Flow at Kuirau Park in 1993 (tonnes/day)	1,728	1,382
Heat Flow at Ngapuna in 1990 (MW)	77	74

Water Level Increase 1986 to 1990 (M)		
M1	1.1	1.1
M6	1.6	1.6
M9	2.3	1.7
M12	0.9	0.7
M16	1.9	1.9

8   Current State of the Rotorua Geothermal Field

An issue that was raised by Environment Bay of Plenty regarding the Rotorua geothermal field was:

> *Is the actual field recovery different to what was anticipated as a result of field management policies in the plan? There is the issue of water level increases in some geothermal aquifer monitoring wells that are above what was predicted. Kissling (2000) identified this trend in some of the monitoring wells from his analysis of the field monitoring data. This prompted Environment Bay of Plenty to revisit the geochemistry of the field to assess whether changes have occurred at depth in the aquifer that might explain the anomalous water level increases in some monitor wells.*

Overall the field seems to be in a stable state with small variations in water levels which are presumably in response to climatic events. However, the water level in M12 appears to be increasing with no identifiable cause. In Section 11.7 we discuss the response time of the system to the Bore Closure Programme, and suggest that water levels take about 3 years to equilibrate after an event. So it is unlikely that the continued rise of the water level in M12 from 1995 is a delayed response to the Bore Closure Programme of 1986-7. As shown in Figure 32, the model suggests that with the current production and reinjection rates, the water levels in M12 should be relatively constant from 1995 to 2004.

This increase in water level observed in M12 could be explained by increasing the upflow into the model under Kuirau Park by 3,800 tonnes/day from 1996. Assuming such an increase allows the model to fit the water levels in M12 and is consistent with increases observed in thermal activity and geothermometer temperatures at Kuirau Park But the cause of such an increase cannot be explained.

We recommend close monitoring of the M12 water levels and surface activity at Kuirau Park, and if these continue to increase then some intervention may be necessary.

Conclusion: Mostly the recovery of the field follows a pattern anticipated as a result of field management policies. The recovery is greater in some parts of the field than anticipated in the model. The cause of this recovery has yet to be verified.

9   Summary

The 1994 model was developed to test various withdrawal scenarios on outflows from the field. This provided an acceptable match to the available data and successfully matched the response of the heat flow at Whakarewarewa and Kuirau Park to changes in withdrawal as result of the 1986 closure programme. However the model match to some of the new monitoring data was found to be inadequate.

An updated version of the 1994 model of the Rotorua geothermal field was developed. The 2004 model uses smaller grid blocks, covers the surrounding groundwater and approximates the regional topography. These improvements over the 1994 model provide a better representation of the conceptual model. The new model gives a good overall match to the response to the 1986 bore closure programme.

The model did not predict recent increases in water levels seen in M12 near Kuirau Park and at M16. However rerunning the model with extra inflow into the northern area of field provided a better fit to monitor well data. This would suggest that there might be extra inflow into the field near the Kuirau Park area. The cause of this phenomenon cannot be readily identified.

Overall the new model of the field provides a good match to observed data and can be used with confidence as tool for making field management decisions.

9.1   Recommendations

1. The monitoring data being collected from M12 should be closely followed. If water levels in M12 and surface activity at Kuirau Park continue to increase then a plan for further investigations should be developed.

2. The well monitoring data being collected for Environment Bay of Plenty is extremely valuable and provides a basis for understanding changes that may occur in the field. EBoP should consider collecting similar information on heat and mass flows at Whakarewarewa and Kuirau Park. For instance, the heat flow survey that was conducted in 2000 could be repeated on a regular basis to provide an on-going record of outflow in the field.

10 References

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Appendices

11 Summary of Data Used to Form the Conceptual Model

Considerable effort has been applied to the task of developing a conceptual model of flow in the Rotorua geothermal field. Since the early 1980s a large amount of information that has been collected by a number of organisations: the Bay of Plenty Regional Council, the former Department of Scientific and Industrial Research, and central Government Ministries. This data has been summarised in a number of publications including *RGMP (1985), Geothermics (1992) Grant-Taylor et al (1992)* and *Gordon et al (2001)*. It is not the purpose of this report to reproduce all this data, but some of the more relevant data is presented here to assist the reader.

In addition to providing the basis for the conceptual model, these data were also used to calibrate the models and validate the output. Figure 2 to Figure 7 and Figure 38 through Figure 50 summarise some of the important information collected at Rotorua.

Information used to form the conceptual model of the system includes:
- The geological structure
- Electrical resistivity
- Heat and mass flows from springs and streams
- Fluid chemistry
- Isotopic composition of fluid
- Well temperatures
- Regions where boiling occurs
- Pressure and waterlevel data
- Pressure changes in response to withdrawal
- Temperature changes in response to withdrawal

We now review some of the data that is available and how it was used in developing the conceptual model. To maintain consistent comparisons with other work, these data will be presented as contours at 180 m.a.s.l. – a depth of about 120m.

11.1 Reservoir Size

The temperatures and resistivity measurements show the reservoir contains a region of hot geothermal water of approximately 20 km^2 in extent as shown in Figure 37. Hot temperatures have been observed at depths of 500m, but it is highly likely that the reservoir extends to a much greater depth.

11.2 Pressures

Only a few pressure or water level measurements were made before significant levels of production occurred, and these are shown in Figure 38 together with contours of reservoir pressures at 180 m.a.s.l. from 1985. The natural state pressures were calculated from measured water levels and

the 1985 pressures were formed from well pressures and water levels, and corrected to the reference depth of 180 m.a.s.l. Details of the procedures used to construct these data sets are given in *Grant et al (1985)*.

Figure 37: Extent of Rotorua Geothermal Field as defined by resistivity surveys. The map is taken from Gordon et al (2001).

11.3 Temperatures

The reservoir temperatures are more difficult to derive from downhole temperature profiles than the pressures. Ideally the state of a well and its surrounding neighbours should be known in order to understand the relationship between the well and reservoir temperatures. Unfortunately this information was not always available, which makes interpretation of the data somewhat difficult. *Isles (1982)* and *Wood (1985)* have studied the temperature data, and their work show similar sets of contours at 180 m.a.s.l. with Wood's contours shown in Figure 39.

Although few natural state temperatures exist, from the few measurements that were made and the temperatures in the 1980s we expect that in the natural state the reservoir showed:
- Temperatures of up to 180^oC near Whakarewarewa
- Lower temperatures to the north and east
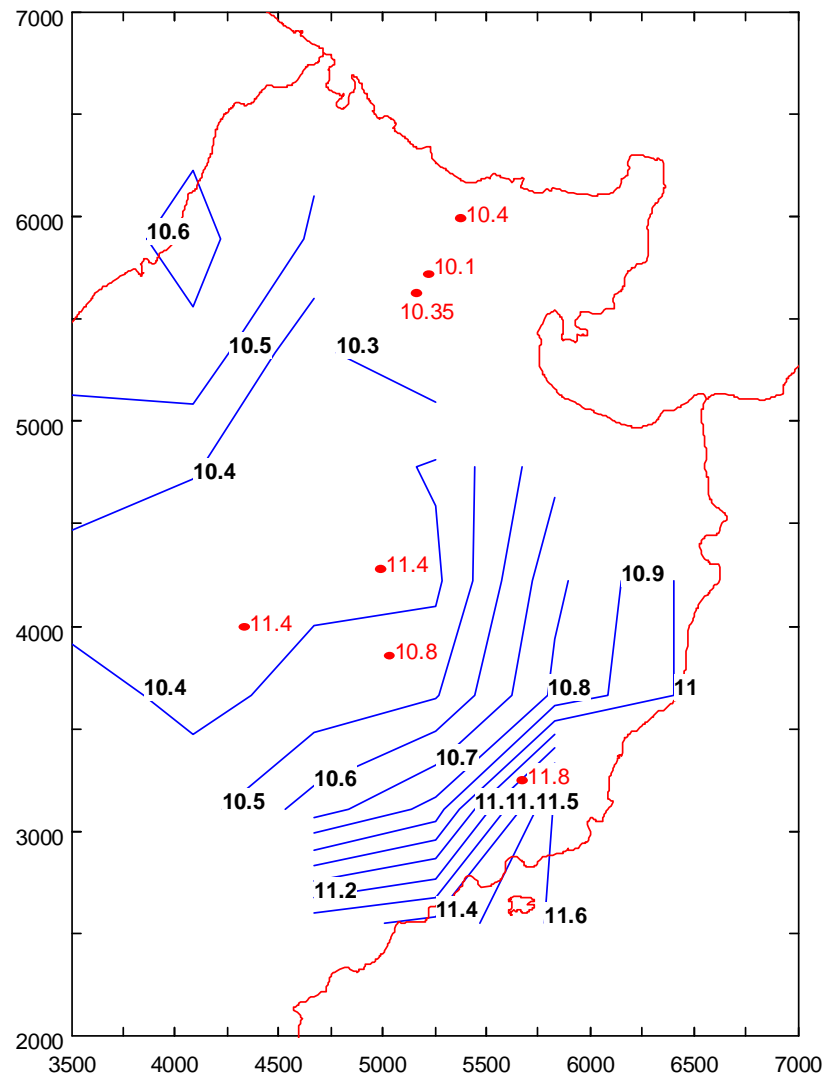
Figure 38: Calculated pressures (bars) at 180 m.a.s.l. after *Grant et al (1985)*. The red numbers are pressures from before 1960, and the blue contours are from 1985
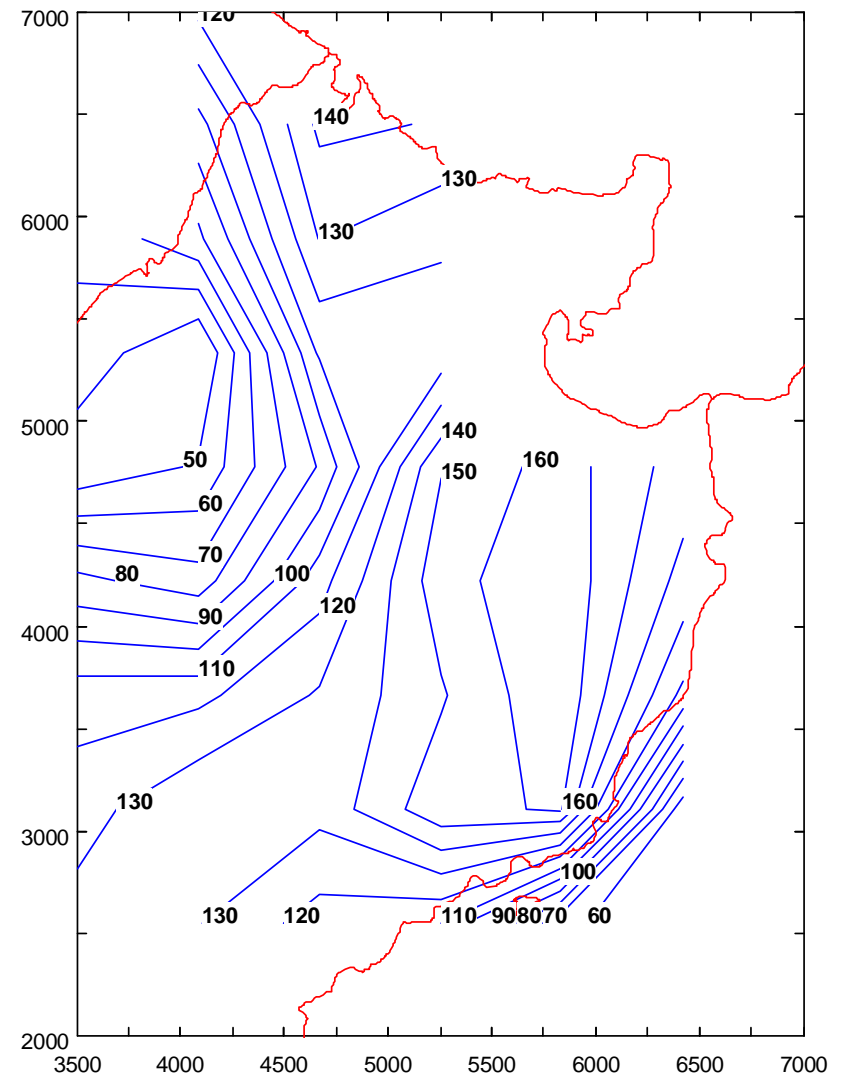
Figure 39: Contours of measured temperatures at 180 m.a.s.l. in 1985 after Wood

11.4 Geology

The geological structure of the system plays an important role in this modelling. *Wood (1985)* has described the known features of the system, and those important to this model are:

- the hot shallow aquifer consists of three regions: rhyolite domes, an ignimbrite layer at the bottom of the aquifer, and an overlying sedimentary layer;
- faults which may provide both upflow paths, and impedances to horizontal flow.

These features are shown in the schematic diagram in Figure 40.
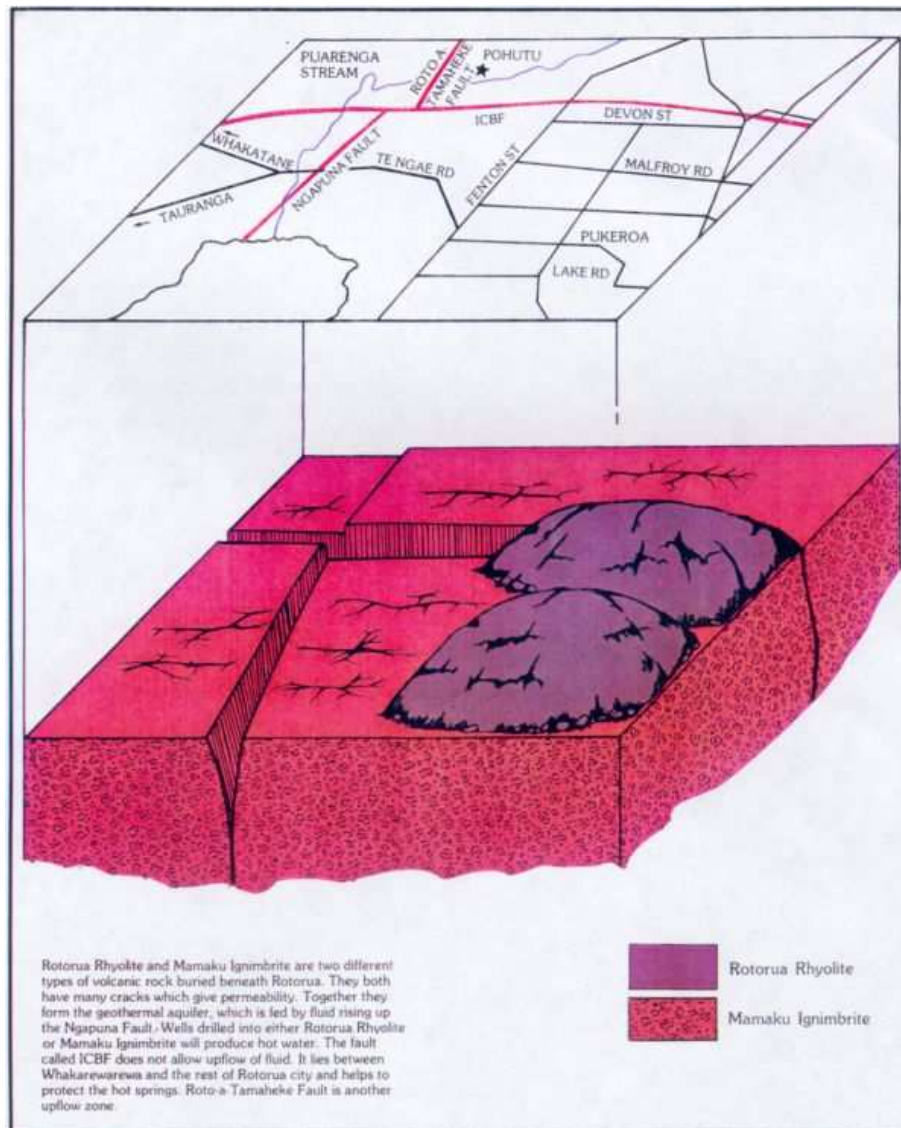
Figure 40: Diagram showing major geological and structural features. The diagram is taken from Gordon et al (2001).

The rhyolite domes in the west, the underlying ignimbrite and the sedimentary layer divide the aquifer into three geologically distinct regions. Wood states that the rhyolite and ignimbrite offer good permeability, especially near their surfaces. *Thompson (1974)* has described the rhyolite as sometimes cavernous. The sedimentary layer is generally regarded as less permeable, although individual beds with good permeability may be present. Contours of the surface of the rhyolite domes are shown in Figure 4, with the surface extending from 280 m.a.s.l. in the centre down to

180 m.a.s.l. at the sides. The ignimbrite is known to exist in the south and east with the surface dipping from 200 m.a.s.l. in the south to 50 m.a.s.l. in the north-east.

A number of faults have been identified in the geothermal aquifer, and are believed to provide permeable paths for upflow of deep hot fluid. These faults are also shown in *Wood (1985)*, and the influence of these faults on fluid flows is shown in Figure 5. The Inner Caldera Boundary Fault is thought to act as a permeability barrier between the ignimbrite in the south and the rhyolite in the north.

Little information on the permeabilities is known. Some pressure and interference tests have been performed, but the reliability of the tests is unclear. Typically they show values of permeability depth, *kh*, between 10 and 100 darcy-metres. So, with a nominal aquifer depth of 100 metres, permeabilities may be of the order of 1 darcy.

11.5 Inflows and Outflows

The surface heat flow from Whakarewarewa is a key measurement for the model to match. The various monitoring programmes have provided measurements of mass and heat flows from many of the features at Whakarewarewa. Heat flow surveys were conducted in 1967 and 1984 and are reported in *Cody and Simpson (1985)*. These surveys measured evaporation, radiation and surface discharge from springs and geysers, a ground surface heat flux and seepage into the bed of Puarenga Stream. The 1967 survey gave a total heat flow of 229 MW. In the 1984 survey the total heat flow had reduced by 31% to 158 MW. These heat flows of 229 and 158 MW correspond to upflows of approximately 290 and 200 kg/s (25,056 and 17,280 tonnes/day) of hot aquifer water at 180ºC.

Grant et al (1985) inferred a heat flow of 300MW in the natural state, corresponding to 400 kg/s (34,560 tonnes/day) of aquifer water. This calculation relies on the change in pressure from the natural state, which is only an estimate. So, the actual value of the heat flow from Whakarewarewa in the natural state cannot be determined with certainty.

In 2000 a new survey was carried out of some of the features at Whakarewarewa and is reported in *Gordon et al (2001)*. This new survey only measured the heat flow from 28 springs in the Whakarewarewa area, compared with 285 in 1984. The survey of 2000 shows that the 28 springs have a combined heat flow of 19MW, compared with 14.3 in 1984 and 20.1 in 1967. If the changes in these springs are representative of the overall change at Whakarewarewa then an estimate of the total heat flow from Whakarewarewa in 2000 is 216 MW.

This figure for heat flow in 2000 may be an underestimate. *Grant-Taylor et al (1992)* report that the flow, inferred from chlorides, into Lake Roto-a-Tamaheke showed an increase of 66%, from 35 kg/s (3024 tonnes/day) in 1984 to 50 kg/s (4,320 tonnes/day) in 1990. Applying this 66% increase to the 1984 heat flow of 158MW gives a heat flow of 260MW. So we have two measures of an increase in heat flow from different parts of Whakarewarewa. Both measurements show an increase in heat flow since 1984 with a larger increase at Lake Roto-a-Tamaheke than the 28 surveyed springs. The current total heat Whakarewarewa flow is unknown but is probably between 216 and 260 MW.

There are known to be flows from the geothermal aquifer into the Puarenga Stream. *Glover (1992)* reports the chloride flux between FRI and the "Dump" site was 42.7 g/s in 1990. This chloride flux had an associated heat flux of 77MW.

At Ohinemutu/Kuirau Park, flows had nearly ceased by 1985. After the 1987 Bore Closure Programme a hot overflow (70-80ºC) from the lake of between 7 and 60 kg/s (600 and 5,180 tonnes/day) was observed in 1993. If this flow is being fed by an upflow from the geothermal

aquifer at 140°C, then this upflow of hot geothermal fluid is between 3 and 30 kg/s (259 and 2592 tonnes/day).

11.6 Chemistry

The chemistry of the fluid in Rotorua has been summarised in *Glover and Heinz (1985)* and *Stewart et al (1992)*, and shows a complex pattern in the distribution of chlorides and bicarbonates. The chloride distribution is consistent with the temperature profiles, with higher values in the east, decreasing as one moves west. Chloride concentrations from wells in 1989 are shown in Figure 41. It should be noted that, in general, the wells in the west are drilled to shallower depths than the wells in the east, and consequently the contours in Figure 41 do not correspond to a single elevation.
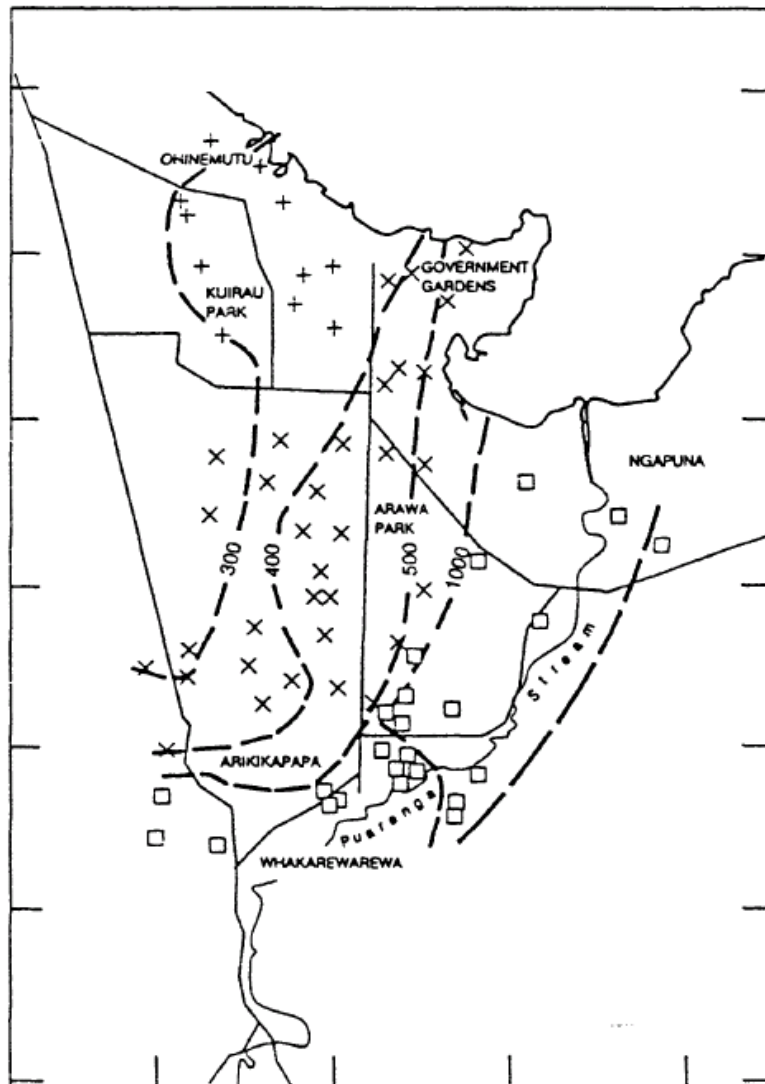
Figure 41: Chloride concentrations from 1989 in ppm from Stewart et al (1992)

11.7 Response to Production

Quantifying some of the changes that have occurred in the aquifer since production started is not a simple task. Since limited information about the natural state is available, it is difficult to assess changes from the natural state. Even changes that have occurred since production began are subject to significant uncertainties since many of the changes are small. An important example is reservoir

pressure. It is believed, *Grant et al (1985)*, that the pressure change in the aquifer from the natural state until 1985 was between 0.2 and 0.5 bar. But the uncertainty in the initial pressure is approximately 0.2 bar.

Even the response of the reservoir to the closure programme contains some uncertainties. Pressure responses are known, through water levels in a number of monitor wells, *Gordon et al (2001)*. Measurements have been made of heat flows from some of the springs at Whakarewarewa, and information has been collected about the state of some of the features there. But there have been no measurements made of changes to heat and mass flowrates from all the surface features.

Bradford (1987) and *Kissling (2000)* have presented water level changes in monitor wells. Figure 43 to Figure 47 show some of this data as an average relative water level, where the average is formed on a yearly basis. The approximate locations of the monitor wells are shown in Figure 42.
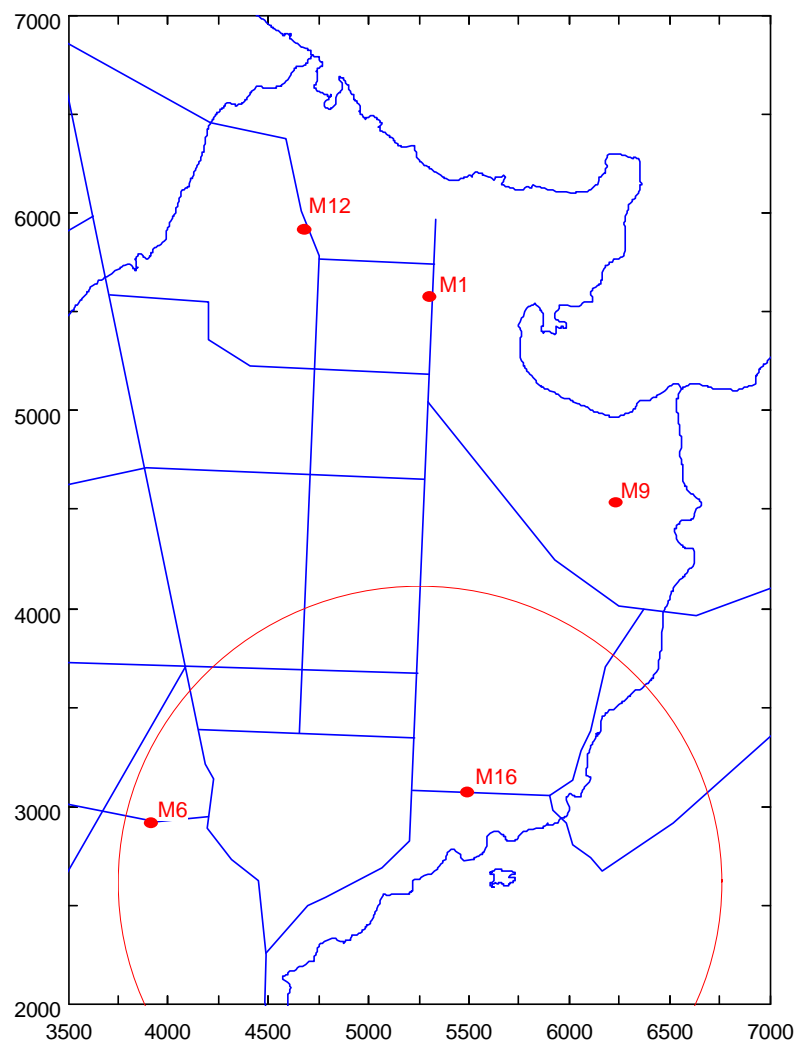
Figure 42: Approximate locations of some of the monitor wells and the 1.5km closure zone
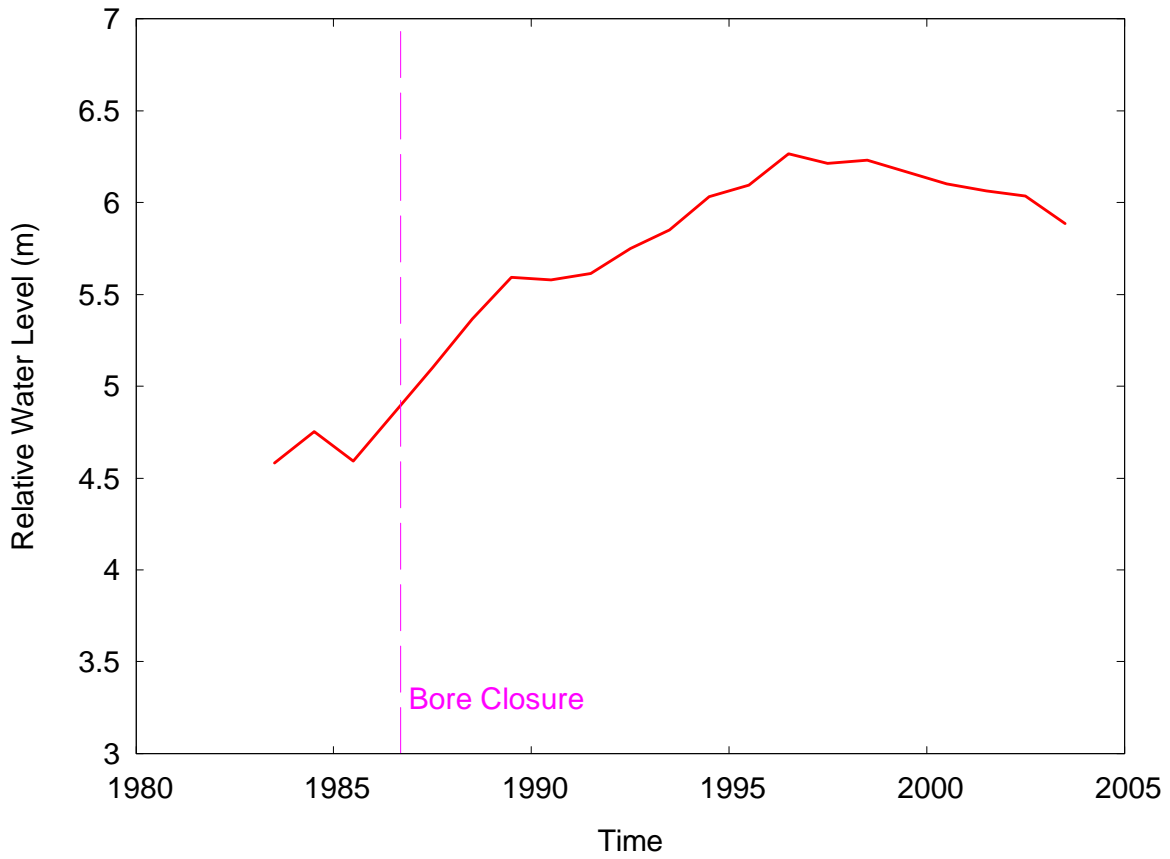
Figure 43: Yearly relative water level average for M1
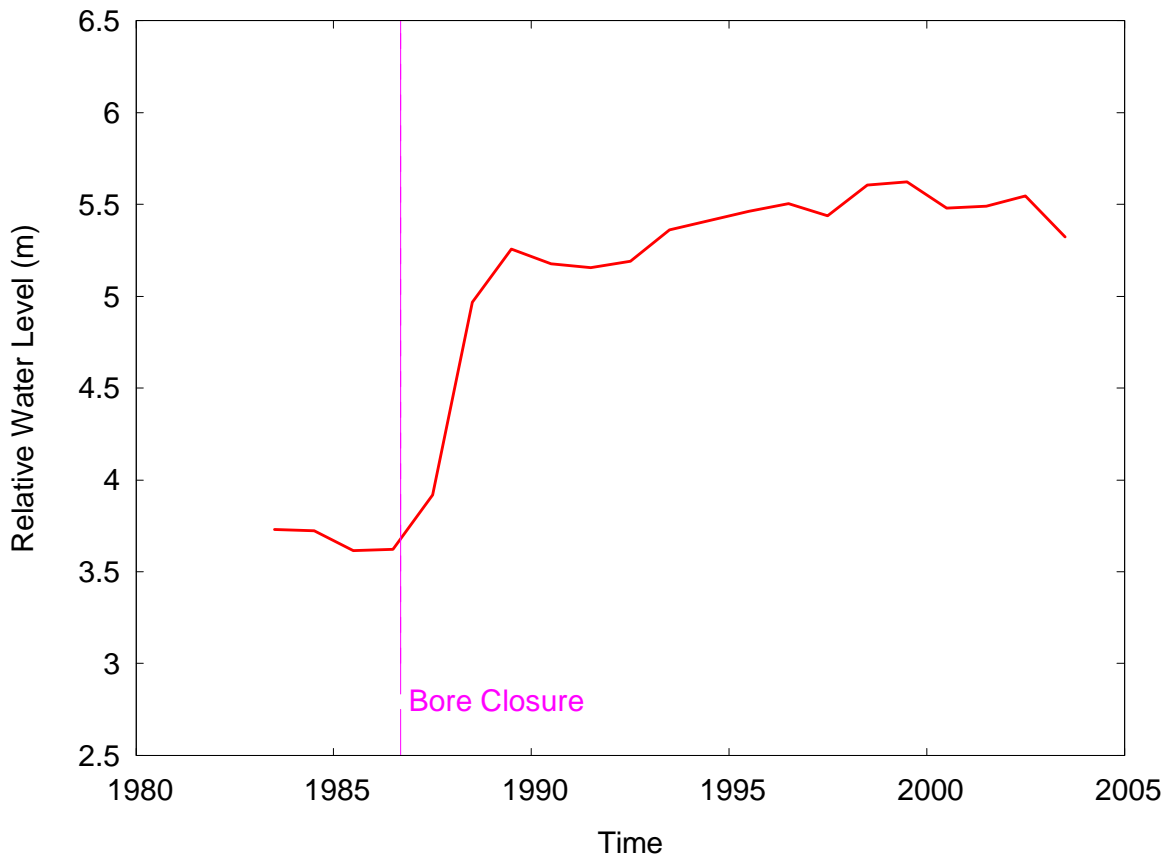
Figure 44: Yearly relative water level average for M6
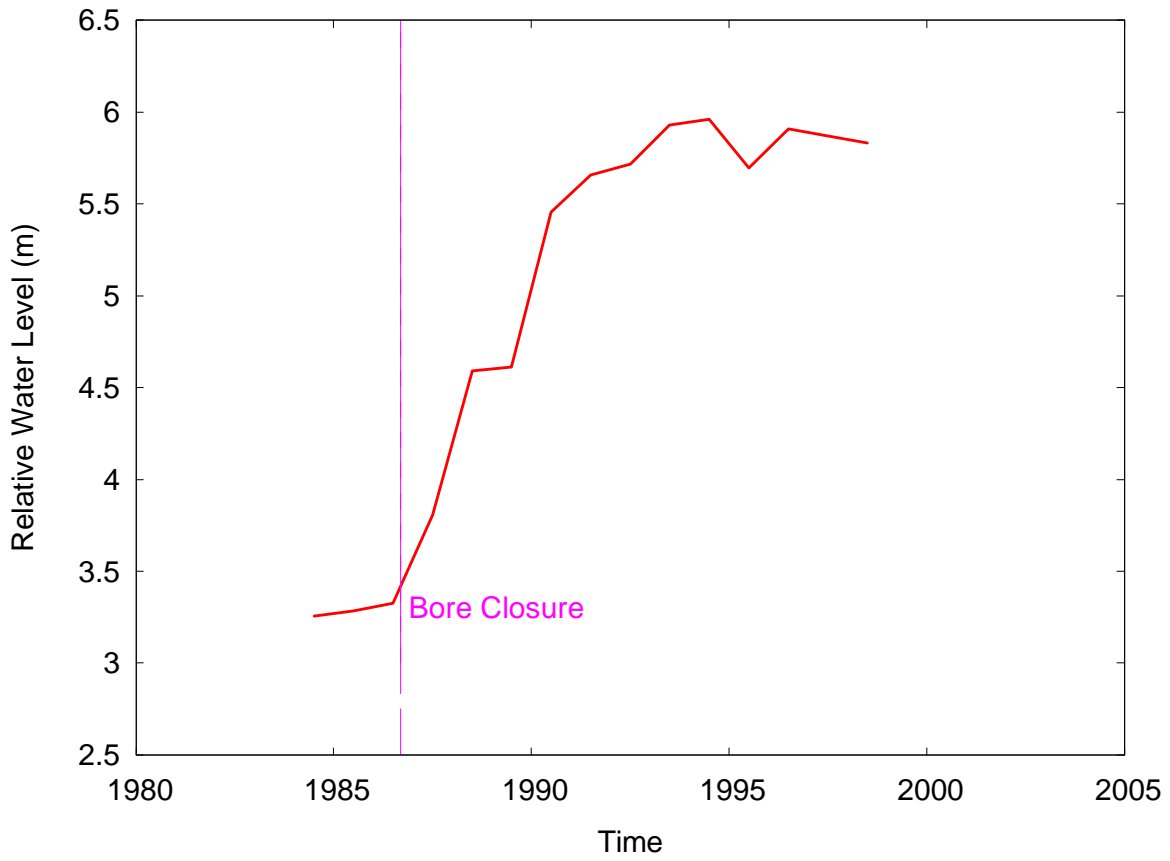
Figure 45: Yearly relative water level average for M9
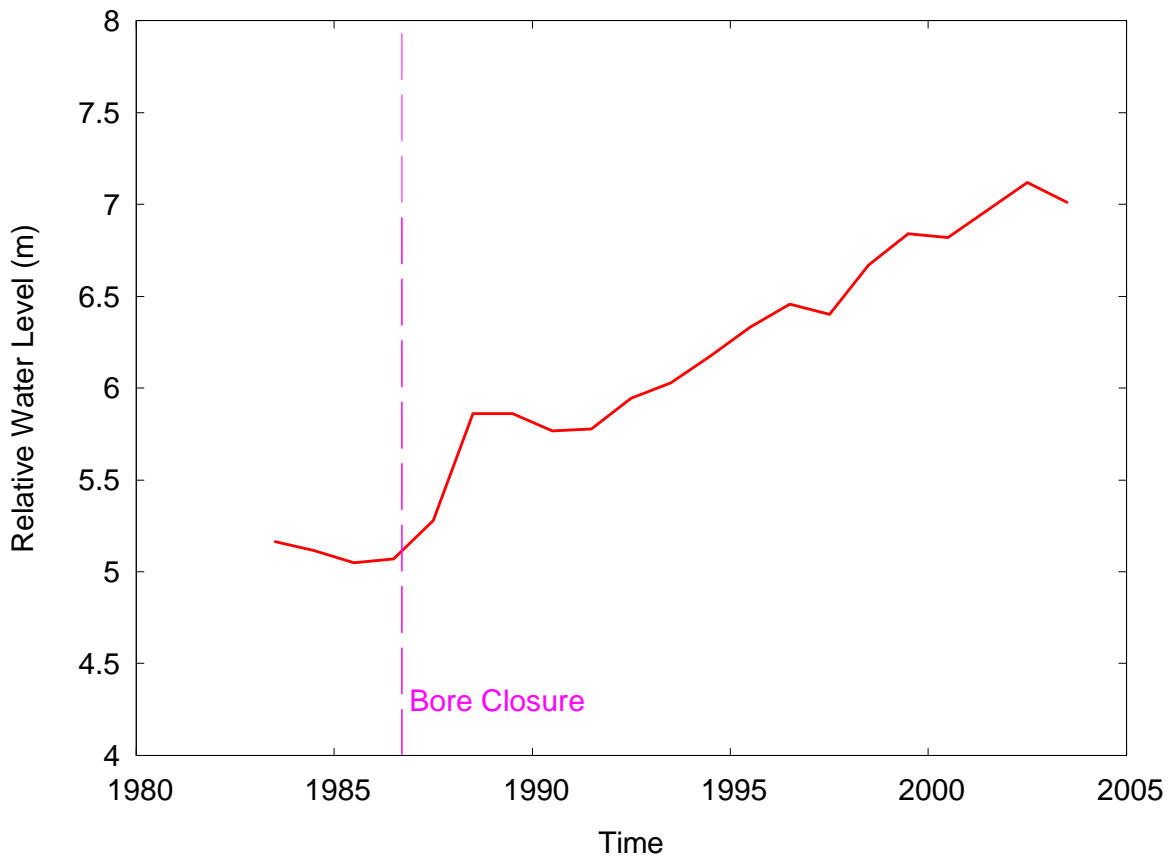
Figure 46: Yearly relative water level average for M12
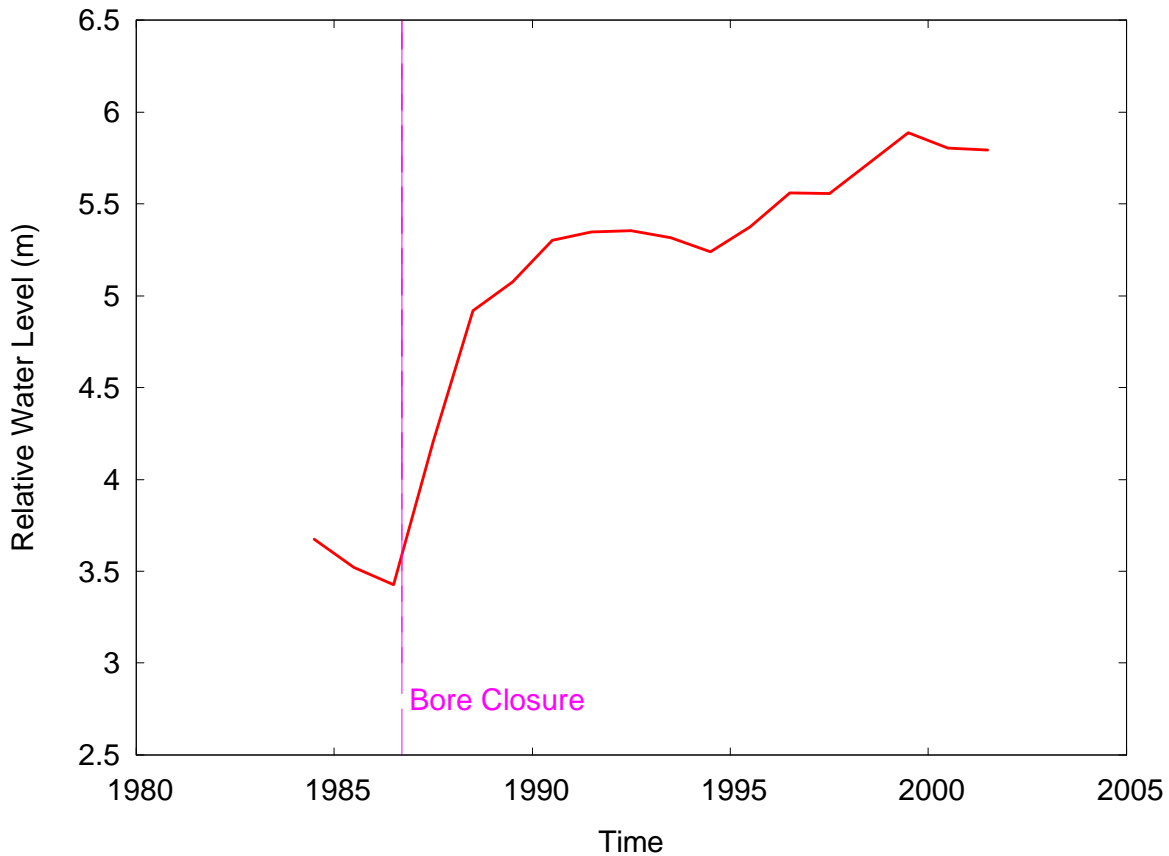
Figure 47: Yearly relative water level average for M16

From these graphs a number of features are immediately apparent:

- Generally water levels were decreasing before the 1986 Bore Closure Programme.
- Between 1986 and 1988 all wells showed significant increases in water level.
- Further overall increases were seen between 1990 and 1995 in all wells
- M12 and M16 showed further increases from 1995

The increase in water levels between 1986 and 1988 is almost certainly the result of the Bore Closure Programme. Between 1986 and 1988, the net withdrawal reduced from approximately 28,000 tonnes/day to 8,000 tonnes/day. The water levels increases over that period seen in Figure 43 to Figure 47 are summarised in the following table:

Table 3: Water level increase between 1985 and 1990, and 1990 and 2000.

Well	Water Level Increase (m)	
	1985 to 1990	1990 to 2000
M1	1.1 m	0.5
M6	1.6 m	0.4
M9	2.3 m	> 0.4
M12	0.9 m	1.0
M16	1.9 m	0.5
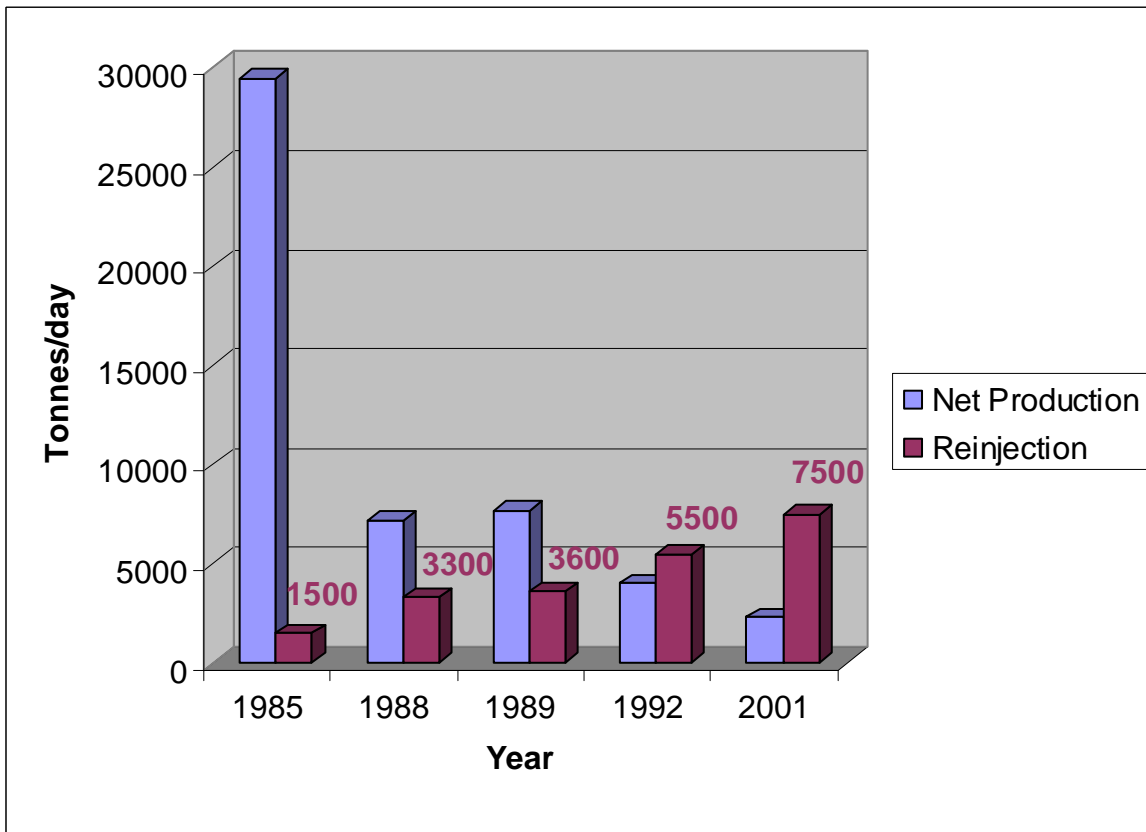
Figure 48: Net production and reinjection between 1985 and 2001
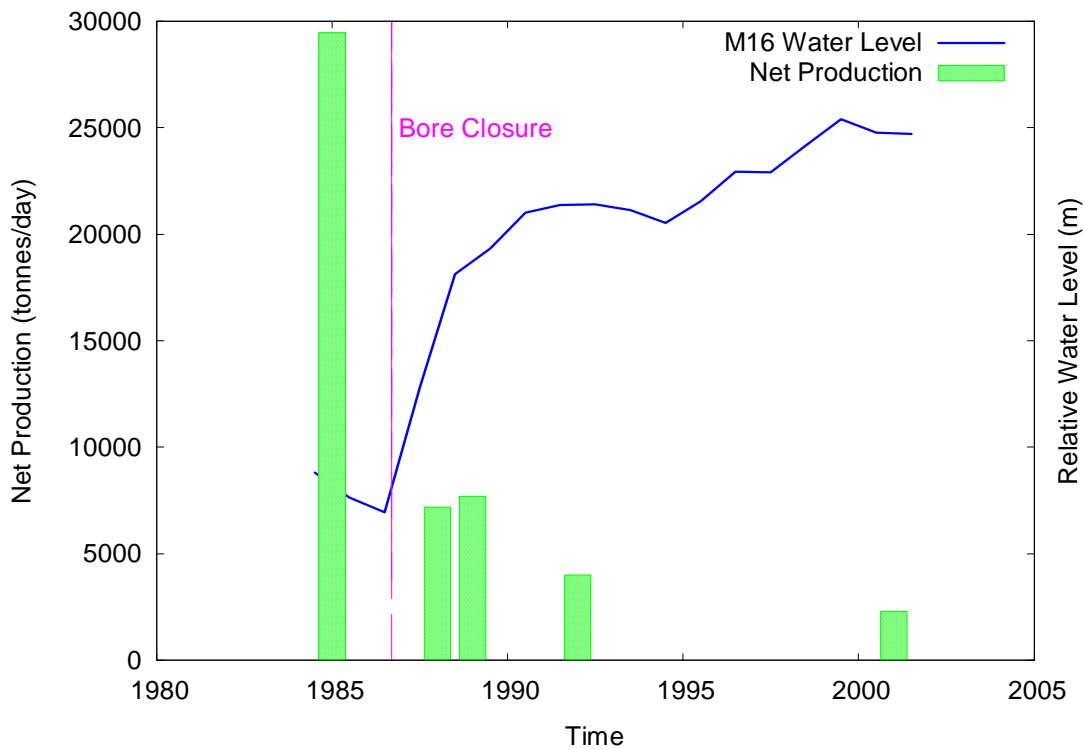
Figure 49: Comparison of net production and M16 water level

Figure 48 and Figure 49 show net production, reinjection and a comparison to the response of M16. Figure 49 shows a large change in water level between 1987 and 1990, however there was little

change in net production between 1988 and 1989. This suggests that M16 responded to the 1987 bore closure for about 3 years. The other monitor wells show a similar response time, suggesting a response time of 3 years to production changes at Rotorua. Between 1990 and 2002, all the wells show a further overall increase. Presumably this is the result of the gradual increase in reinjection that took place from 3,600 tonnes/day in 1989 to 7,500 tonnes/day in 2001.

However the continued increase in water levels in M12 and M16 from 1995 as shown in Figure 50 cannot yet be explained. The water level in M12 has risen by 0.85m between 1995 and 2002 which is comparable to the increase from 1987 to 1990. Yet the increase in M12's water level between 1987 and 1990 was in response to a reduction in net withdrawal of approximately 20,000 tonnes/day. The reduction in net withdrawal between 1995 and 2002 was certainly less than 2,000 tonnes/day. Using a simple linear extrapolation of M12's response to the Bore Closure Programme, a reduction in net withdrawal of 2,000 tonnes/day would produce a water level increase of about 0.1m for M12. Thus the rise in water level at M12 between 1995 and 2002 is higher than anticipated.

During that time the water level in M16 has also increased. Since M16 is about 3 km from M12, it would appear that the water level increase is not a local effect around M12. Exactly what is driving this increase in water level is not clear, especially since the nearby well M1 has shown a decrease over that period.
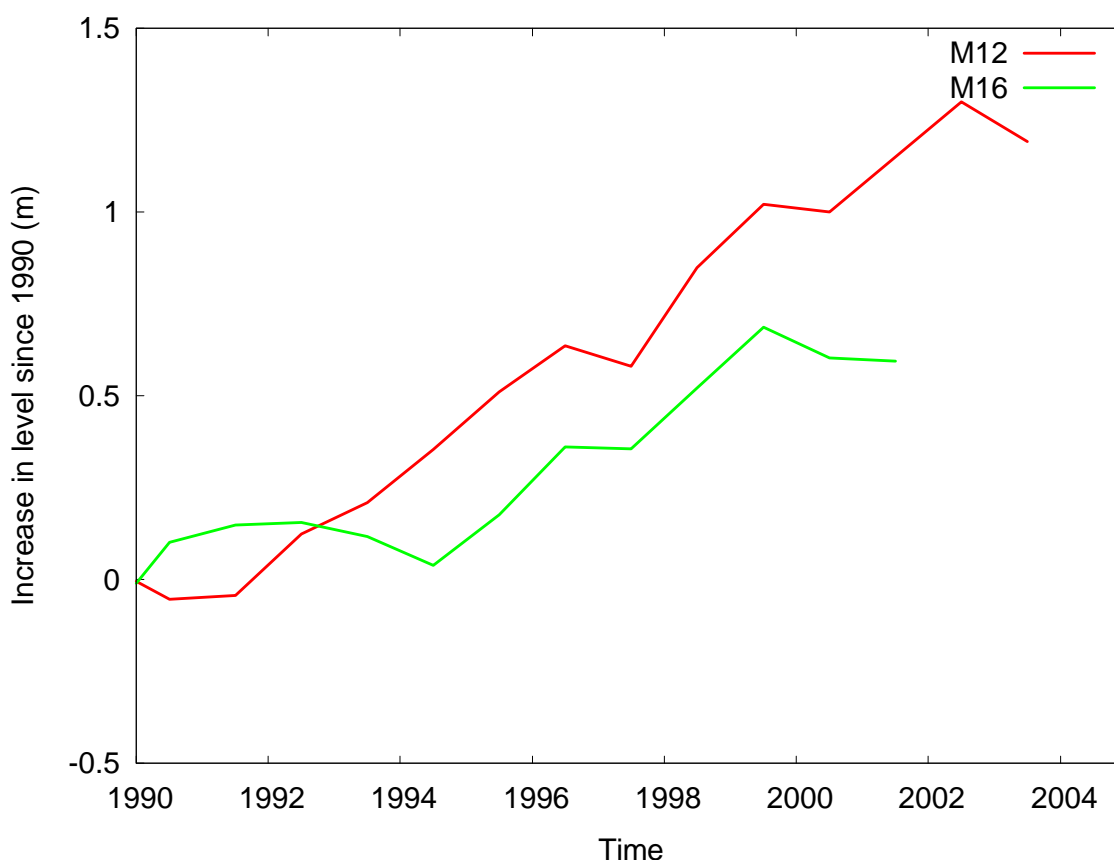
Figure 50: Water level increase since 1990 in M12 and M16

11.8   Conceptual Model

The physical and geoscientific data summarised in the preceding sections forms the basis for development of the conceptual model of fluid flow in the reservoir. The conceptual model of the

Rotorua geothermal field used in this work was based on the model of *Grant et al (1985)* and other relevant data presented in *Grant-Taylor et al (1992)*, *Gordon et al (2001)* and *Geothermics (1992)*.

The conceptual model identifies the important processes that control flow in the system, and its primary features, sketched in Figure 51, are:

- A shallow geothermal aquifer;
- Hot flows into the geothermal aquifer underneath Whakarewarewa, Pukeroa Dome, and along Puarenga Stream;
- An overlying groundwater system with some leakage into the geothermal aquifer;
- Flows to the surface at Whakarewarewa, Kuirau Park and Ngapuna manifested as springs and geysers;
- Flow paths influenced by the geological formations and structures;
- A flow from the south and east to the northwest;
- Interaction between rainfall and spring flows;
- Surrounding colder groundwater which mixes with the geothermal waters;
- A ground surface which falls away moving towards the lake
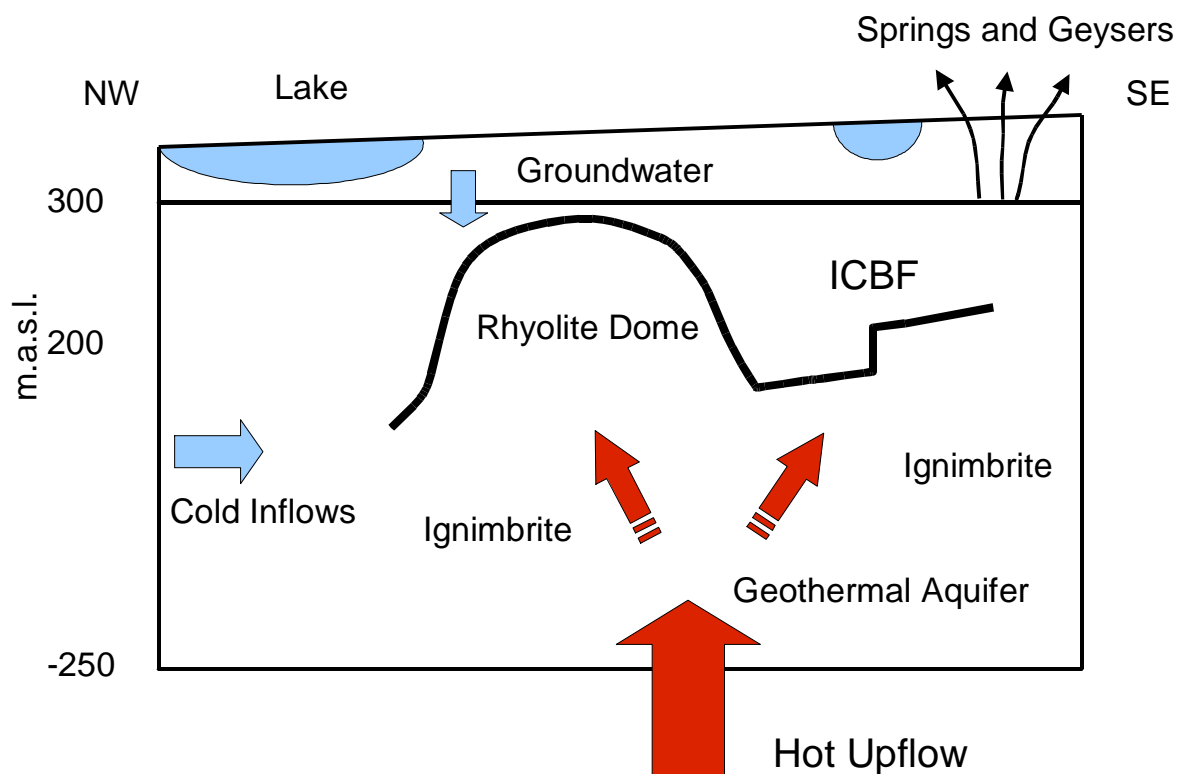
Figure 51: Schematic diagram of conceptual model of flow at Rotorua

The pressure distribution shows that the flow moves from the south and east towards the northwest. A sharp pressure gradient in the south of the field coincides with the Inner Caldera Boundary Fault. The inference that can be drawn from this is that the ICBF is a permeability barrier for north-south flow in the west of the field. Wood has suggested that the permeability barrier may be associated with the edge of the rhyolite. *Simpson (1985)* suggests that the northeast trending Ngapuna and Roto-a-Tamaheke Faults may provide enhanced flow paths across the ICBF from the Whakarewarewa area.

Temperatures suggest areas of upflow under Whakarewarewa, along the Puarenga Stream and at Pukeroa Dome in the northwest. Dilution with cold water occurs in the rhyolite, whereas the temperatures in the ignimbrite are reasonably uniform.

The aim of this work is to develop a computational model of the reservoir, which can address questions regarding the impact of production on surface features. Representing a complex geothermal system with a model requires that compromises be made, but care has been taken to ensure that the model is capable of addressing such questions.

One example of a compromise is that the model hypothesises a shallow geothermal aquifer of about 500m. Undoubtedly the aquifer extends below this, but we have no knowledge of the structure and properties below 500m. The influence of the deeper parts of the aquifer are included in the model as hot upflows. Since our primary concern is changes to the shallow aquifer, such as changes in outflows in response to production changes, modelling the system as a shallow aquifer with hot upflows should be essentially equivalent for this purpose to extending the aquifer to some (unknown) depth. Both approaches require information about the system that is not available. For example, the size of the upflows in one case or the geological structure of the deeper aquifer in the other. We believe that the approach taken here is the best compromise, since the only information required of the extended system consists of mass and energy flow rates together with their locations. As this information can be estimated from measured data, uncertainties in the model should be reduced.

Further simplifications made in the computational model are:
- The spring and geyser flows are assumed to be only dependent on the reservoir pressure as shown in equation (2) of Section 13. This simplification was made due to limitations in the computer simulator. Since most of the flow from Whakarewarewa is from springs this is likely to be a reasonable approximation. However it does mean that effects on the most visible features, namely the geysers, cannot be modelled accurately since these almost certainly depend on the temperature and may be affected by local features such as terrain conditions.

- Lake Rotorua is not directly included in the model since the nature of the interaction between the lake and the geothermal system is unclear. The boundary condition used in the model allows for flows from the geothermal aquifer into the cold groundwater to the north and vis-versa.

12 Model Description

The model described here was solved using a modified version of the TOUGH2 computer program to simulate the reservoir behaviour. This program was originally developed at Lawrence Berkeley National Laboratory (*Pruess (1991)*) and has been used throughout the world to model geothermal and groundwater problems. The program solves the equations describing the flow of heat and mass in a porous medium. Modifications were made at Industrial Research Limited to improve the handling of large grids. The modified version of TOUGH2 has been tested against a suite of test problems.

The simulations carried out here used a module that allows water in its liquid and vapour phases, heat, salt and air to flow in a porous medium. The equations for this module are given in equation (1) of Section 13. These simulations require the following input:

- A 3-D computational grid covering the system;
- The specification of rock properties in each grid block, including permeability, porosity, specific heat, and conductivity;
- Prescribed boundary pressures, temperatures and chloride concentrations;
- Any inflows and outflows that occur in the system
- Injections and withdrawals that are imposed on the system

12.1 Grid Structure

The model is a 3-D model that covers the Rotorua Geothermal Field and its surroundings. The model is built from 7 horizontal layers that start at the ground surface and extend to a depth of 570m. The vertical structure of the model is shown in Figure 12. The grid used in each horizontal layer is shown in Figure 13, and covers the recognised hot shallow aquifer at Rotorua. There are 3550 grid blocks in the model. Near the location of the ICBF, the grid is refined to accommodate the sharp change in rock properties that restricts flow from the south to the north across the ICBF.

12.2 Material Properties

Various estimates of the permeabilities have been made at Rotorua, and they all show a highly permeable aquifer. Interference tests suggest values of the order of one darcy, and previous 2-D models such as *Grant et al (1985)* had effective permeabilities of between 1 to 500 darcys. Also, *Thompson (1974)* notes that the rhyolite is almost cavernous in places. These points suggest that the Rotorua aquifer is highly permeable, which means that there will be fast responses and travel times between connected areas.

Rock properties are assigned to the grid in a manner that approximately represents the geological structure of the aquifer. The material types used in various layers of the model are shown in Figure 14 through Figure 18. The permeabilities corresponding to each of the materials shown in these figures are given in Table 4. In the ignimbrite and rhyolite regions, values were between 0.15 and 5 darcy. At the Inner Caldera Boundary Fault permeabilities were set to resist north-south flow, but allowed east-west flow. In the regions outside the geothermal system, permeabilities ranged from 0.1 to 1 darcy.

Table 4: Material Properties used in the model. The material names refer to the legends in Figure 14 through to Figure 18.

Material	Permeability (darcys)		
	x	y	z
Ignimbrite	0.66	0.98	0.2
Rhyolite	4.8	0.15	10
Fracture	5	17.8	1
South Ignimbrite	0.1	0.02	0.05
East Ignimbrite	0.5	0.5	0.05
West Ignimbrite	0.5	0.5	0.01
North Ignimbrite	0.1	1	0.02
Sediments	0.1	0.1	0.05
West Sedimients	0.5	0.5	0.05
Aquaclude	0.01	0.01	0.001
ICBF	0.1	0.001	0.1
ICBF Lower	0.1	0.1	0.1

In order to match the observed response to extraction, it was necessary to include a highly permeable connection between Whakarewarewa and the downtown area, with a permeability of 18 darcy. The decline in outflow observed at Whakarewarewa of about 13,000 tonnes/day in response to a total production of 30,000 tonnes/day, could only be explained by the existence of such a channel. This channel could correspond to a fault or a large fracture-like structure along the interface between the rhyolites and ignimbrites. Sometimes high permeabilities are found along such interfaces.

12.3 Boundary Conditions

The model is open along the north and south sides. That is, along these sides fluid can flow between the modelled area and the surrounding groundwater. The boundary at the north represents the lake and groundwater, this boundary is able to accept outflow from the field, and provide recharge from the lake. The boundary to the south represents pressure control provided by the hills behind Whakarewarea and drives a regional flow from the south to the north. Pressures in these boundaries were assigned from consideration of hydrostatic columns of cold water. On the southern boundary, the pressures were 3 bar higher than the northern boundary. Temperatures at both boundaries were cold conditions of around 15ºC. These boundary conditions were held constant throughout the simulation.

At the top surface, blocks of air at 1 bar and 15ºC were placed. The east and west boundaries of the model were closed, as was the bottom of the model except for regions where inflow occurred.

12.4 Spring and Geyser Model

The spring and geyser model used a simple approximation where the flowrate is proportional to a difference between the reservoir pressure at a prescribed depth and a prescribed pressure. This simple approximation is described in Section 13. This approximate model can be realised by placing wells on deliverability into appropriate grid blocks. These outflows are located at Whakarewarewa, Kuirau Park and Ngapuna, and are shown in Figure 52.

Predicting outflows from geothermal systems can be difficult, but this approximation for spring and geyser flow is suitable for the Rotorua model. Difficulties in modelling outflows have been encountered at Wairakei where the heat flow from the Karapiti area increased from 40 MW to 400 MW as a result of production. In that case pressures dropped in the reservoir by about 20 bar, which resulted in considerable boiling. As a result, steam rose and escaped at Karapiti. But that type of situation is completely different to Rotorua. At Rotorua, pressures dropped by a relatively small amount in the reservoir, and this fall in driving pressure resulted in a fall in outflow at Whakarewarewa and Kuirau Park. Such behaviour is captured reasonably well by the linear model used here.
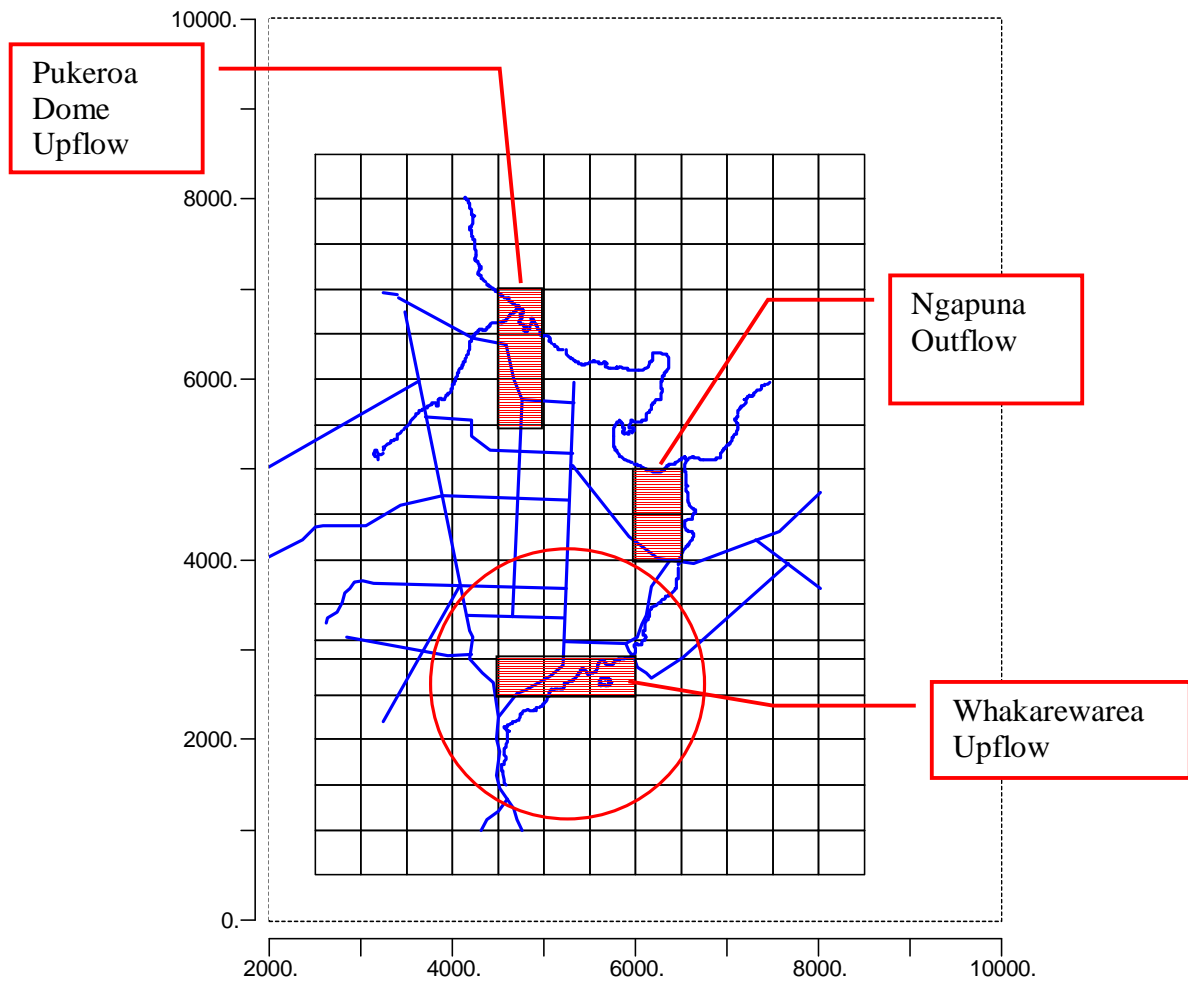
Figure 52: Location of wells representing springs and geysers in the Whakarewarewa and Arikikapakapa areas, Ngapuna and at Kuirau Park

12.5 Inflows

Heat and mass inflows were modelled using sources placed on the bottom layer. The blocks where these inflows were located are shown in Figure 53. The inflows were adjusted until the model outflows and temperatures approximately matched those of the natural state. The main inflows were sited under Whakarewarewa and along Puarenga Stream. A further inflow was placed under Pukeroa Dome as the chemistry suggested that there is a separate flow in this region. The flow rates assigned to each inflow in the natural state are shown in Table 5. These flow rates were allowed to increase as pressures in the reservoir declined.

Table 5: Mass inflows in the natural state used in the model

Location	Amount (Tonnes/Day)	Temperature
Whakarewarewa	30,320	200ºC
Puarenga Stream	17,300	220ºC
Pukeroa Dome	2,420	200ºC

In addition to upflows at the bottom of the model, rainfall was included in the model. In the upper layer of the model, 13,800 tonnes/day was injected uniformly over the modelled area. This corresponds to an infiltration rate of about 7.5%.
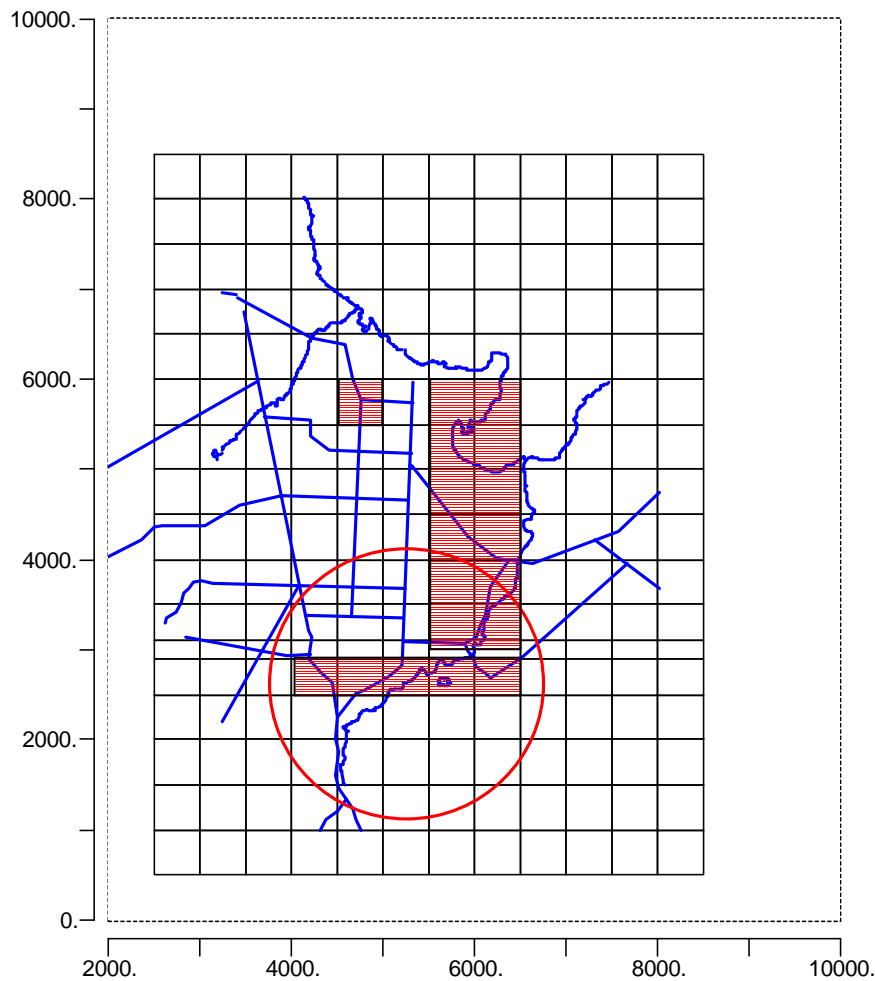
Figure 53: Location of wells representing inflows into the system in the bottom layer. The shaded areas show inflows under Whakarewarewa, Puarenga Stream and Pukeroa Dome.

12.6 Model Calibration

Calibration of the model was performed by choosing trial values of the model parameters, and then adjusting their values so that the model results matched measured data from the aquifer. The model was calibrated against data collected before 1992; primarily because the greatest changes were seen in the system over that period. Specifically, the model results were compared to:

- pressures in the natural state, and in 1985;
- temperatures in 1985;
- outflows at Whakarewarewa in the natural state and in 1985;
- pressure changes from 1985 to 1992;
- chloride concentrations in 1989;
- boiling regions in 1985.

The unknown parameters in the model are:
- the permeabilities
- the mass and heat inflows together with their locations
- and the coefficients in the spring and geyser model.

12.7 Differences to the 1994 Model

The model described in this report is an update of the 1994 model described in *Burnell and Young (1994)*. Since the 1994 model was developed, computational resources have improved significantly. Consequently it now possible to build larger and more complicated models which represent the conceptual model more closely. The model described in this report includes the following improvements:

- The model covers a larger area. Areas of cold groundwater are now included in the model. In the 1994 model groundwater was only included through boundary conditions prescribed on the sides of the model. The model results are no longer dependent on prescribing the interaction between the groundwater and hot aquifer.

- The model extends vertically to the ground surface and includes overlying groundwater and atmospheric blocks. The 1994 model had a closed top below the groundwater.

- The lateral boundary conditions have been improved. In the 1994 model, pressures were prescribed along the east and west boundaries. These pressures are no longer prescribed. With the increased horizontal extent of the model, the groundwater pressures in the east and west are now model outputs rather than model inputs.

- Rainfall is now included into the model. For the results presented in this report a constant annual rainfall was used in the model. However this rainfall can now be adjusted to predict the effect of significant climatic events.

- The number of grid blocks used in the model has increased. The 1994 model had 462 blocks and the current model has 3,550 blocks.

- The model has a more accurate representation of the geology. For example, the sediments overlying Whakarewarewa are now included in the model, the rhyolite domes are more accurately represented, and the ICBF no longer extends to the bottom of the model. This represents the conceptual model shown in Figure 51 more closely than the 1994 model.

- Finally the match to the bore closure programme has been improved in the latest model.

13 Model Equations

The computer program TOUGH2, *Pruess (1991)*, solves the transport equations when water, steam and heat flow in a porous medium, viz:

$$\frac{d}{dt}\int_V M = \int_\Gamma J_M . n + \int_V q$$

$$\frac{d}{dt}\int_V E = \int_\Gamma J_E . n + \int_V q_H$$

$$M = \phi(S_l \rho_l + S_v \rho_v)$$

$$E = (1-\phi)\rho_R C_R T + \phi(S_l \rho_l u_l + S_v \rho_v u_v) \tag{1}$$

$$J_M = -k\left(\frac{k_{rl}}{\nu_l}(\nabla P_l - \rho_l g) + \frac{k_{rv}}{\nu_v}(\nabla P_v - \rho_v g)\right)$$

$$J_E = -k\left(h_l\frac{k_{rl}}{\nu_l}(\nabla P_l - \rho_l g) + h_v\frac{k_{rv}}{\nu_v}(\nabla P_v - \rho_v g)\right) - K\nabla T$$

Where P, T, S, ρ, ϕ, k, k_r, ν, u, h, K, q are the pressure, temperature, saturation, density, porosity, permeability, relative permeability, viscosity, internal energy, enthalpy, thermal conductivity and external sources respectively. The subscripts l, v, H and R denote liquid, vapour, heat and rock respectively. V is an arbitrary flow domain, and Γ its boundary.

This system of integrated partial differential equations is solved for P, T, S using a finite difference formulation. A grid of elements representing different regions in the geothermal system is prescribed, together with any sources or sinks, and the initial conditions for that region. A set of variables representing the average values of P, T, and S over each element of the grid is calculated from the resulting system of algebraic equations.

Accurate models of spring and geyser behaviour will involve a complex combination of conditions in the groundwater layers and the deep reservoir. The precise form of such a model is not known at present, and a simple approximate model for the springs and geysers was used. Such an approximation is unlikely to lead to significant errors in this work, since variations over the time scales of days will affect the steady state of the system. The spring and geyser model that was used has the form

$$F = \alpha\left(\frac{k_{rl}}{\nu_l} + \frac{k_{rv}}{\nu_v}\right)(P - P_{0)} \tag{2}$$

where F is the flow from the aquifer, and α is a recharge conductivity. This model may not provide an accurate description of local changes over short time spans. For the long time scales considered in this work it should adequately mimic the average discharges from the field.