Cover Page

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NUMERICAL MODELLING OF THE EFFECT OF GEOTHERMAL RESERVOIR PRESSURES ON THE ALUM LAKES AT WAIRAKEI, NEW ZEALAND

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SUMMARY – The local groundwater system and surface geothermal features such as geysers, boiling pools, mud pools, and steaming ground at Wairakei, New Zealand, have been strongly affected by 50 years of fluid extraction from the underlying Wairakei geothermal reservoir. For this study we have used geothermal reservoir and surface water data to calibrate a two-dimensional (2-D) numerical model, using the TOUGH2 geothermal simulator (Pruess, 1991), which links reservoir drawdown to changes in geothermal outflow from the Alum Lakes area of the Wairakei system. The 2-D model is derived from an existing three-dimensional (3-D) computer model of Wairakei system, but with a finer grid in the vicinity of the Alum Lakes. The model shows that pressure decline in the Wairakei reservoir has resulted in a cessation of the geothermal upflow to the overlying Alum Lakes, and the Alum Lakes feeder conduit now hosts a down flow of groundwater.

1 INTRODUCTION

Alum Lakes is an area of geothermal activity, including overflowing geothermal springs, at the head of the Waiora Valley, Wairakei. Over the past 40 to 50 years visible spring mass flows have declined to almost zero. This study incorporates details of the Alum lakes area into a 2-D computer model of the Wairakei geothermal system to test the possibility that the decrease in discharge from the Alum lakes is related to declining reservoir pressure.

The model shows that there is an upflow of water and steam through a high permeability conduit from the reservoir to the Alum Lakes. As the reservoir pressure decreases, the liquid upflow weakens, the steam upflow ceases, and a downflow of groundwater develops in the conduit.

2 DESCRIPTION OF ALUM LAKES

The Alum Lakes area consists of individual geothermal pools and thermal ground (Bromley, 2001 and Bromley and Clotworthy, 2001). Natural state information is provided from Gregg and Laing, (1951) who mapped the extent of thermal ground and the spring details for over 100 springs, including chemistry and discharge, during May –August 1951. Bromley (2001) identified some significant features of the area that have experienced declining water levels and reduced spring flows in the last 50 years. In order of descending elevation they are:

2.1 Pirorirori

Pirorirori (#403) is the largest individual feature, and the source of the Kiriohineki Stream which drains the area. In 1951 Pirorirori was 47 °C, with a pH of 2.5, and an outflow of 11 l/s. Visible inflows to the lake were two springs on the margin of the lake (#401 and #402) with temperature of 25 °C, a pH of 6, and a combined flow of 15 l/s. These two observations suggest that the lake was steam heated and that a significant proportion of the outflow was subsurface. Pirorirori surface outflows are thought to have stopped by the mid 1990's, although the confirmed data has zero flow at January 2001. The level of Pirorirori did not change significantly between 1951 and 2001; however, since 2001 the lake level has dropped by over 3 m and the Kiriohineki Stream ceased to flow.

2.2 The Mudflat area

This is an area of thermal ground and acid pools. There appears to have been little liquid discharge from this area, although water levels have declined at a rate of about 1 m/year between 1997 and 2000, and temperatures have declined from 52-57 °C to 36-42 °C over the same time.

2.3 Butterfly Spring

The Butterfly Spring (Heavenly Twins), was two pools {Gregg and Laing, 1951) which have subsequently merged into one. The combined discharge from these springs in 1951 was 7.5 l/s. The Butterfly Spring was observed to have ceased flowing by 1997, but there is no record of when the discharge actually stopped, although the flow has now ceased.

2.4 Devils Eyeglass

The Devil's Eyeglass springs continued to flow between 1951 and 1997, but the chloride content has decreased from 667 mg/kg in 1951 to 154 mg/kg in 1997, and the flow had reduced from 1.6 l/s to 0.7 l/s, indicating a reduction in recharge from the deep reservoir. By March 2001 the water level in the spring had declined by around

0.15 m, which we have assumed indicates that the spring was not discharging.

3 CONCEPTUAL MODEL

The water of Alum Lakes was originally a mixture of steam, deep chloride water, and groundwater, with a chloride water component of <50% ({Grange, 1955 #1477}, {Glover, 2000 #1523}). A reduction in reservoir pressure has reduced the geothermal inflow to the lakes, leading to a greater groundwater component in the lake waters.

The aim of modelling is to test the conceptual model described above, by reproducing the observed behaviour when a representation of Alum Lakes responds to changes in the Wairakei reservoir.

4 DESCRIPTION OF NUMERICAL MODEL

The model geometry is a two dimensional east-west vertical slice through the main production reservoir at Wairakei, and following the centre of the Waiora Valley (Figure 1). Initially the layer structure, depth, permeability structure, and top and bottom boundary conditions are taken from the existing large three-dimensional model of Wairakei. The horizontal grid of both the three-dimensional and two-dimensional models are shown in Figure 2.

However, the two-dimensional model required some refinement of the grid layers, and modifications to the original permeability structure and bottom boundary conditions. Production was scaled down until the two dimensional model gave similar results to the three dimensional model.

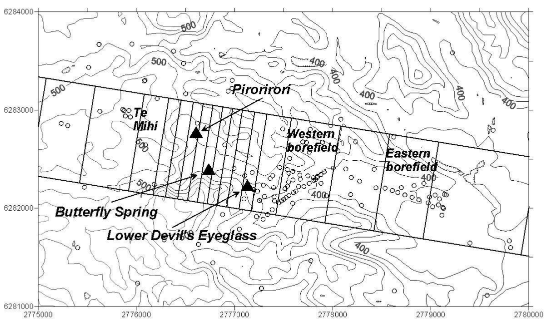


Figure 1. Detail of the Alum Lakes model grid showing the Wairakei Borefields, the individual Wairakei wells (circles), and the features of the Alum Lakes area (black triangles) that have been used to calibrate the model.

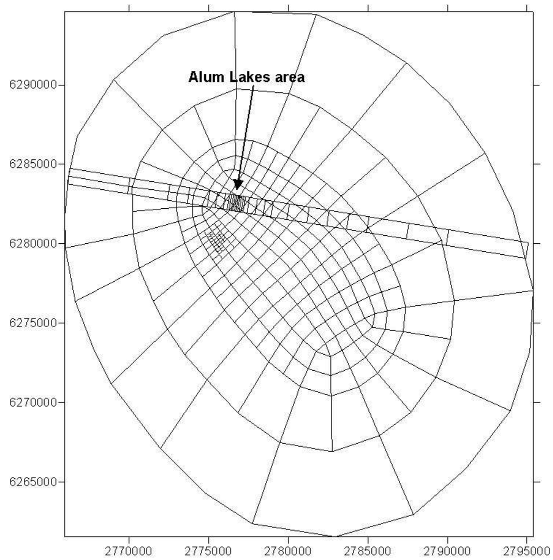


Figure 2. Plan view of the large three-dimensional Wairakei model grid, and the two-dimensional Alum Lakes model grid.

Where the surface intersects the upper and middle Alum lakes area the layers are 2 m thick (Figure 3), except where these were adjusted to match the original water level of the individual springs. The top of column 172 is the water level in the Lower Devil's Eyeglass spring, the lowest of the Alum Lakes springs, where the layer thickness is 12 m.

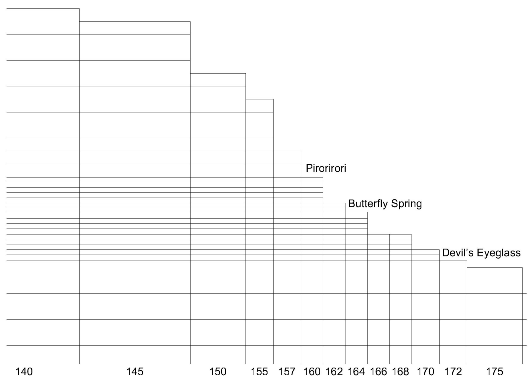


Figure 3. Vertical cross section through the two-dimensional model, detail through the Alum Lakes blocks.

The column structure is necessarily different from the three-dimensional model as the section line crosses the model obliquely (see Figure 2). The columns at the boundary blocks of the model are up to 5000 m wide, reducing to 100 m in the Alum Lakes area. This allows the individual features to be in separate columns; Pirorirori is in column 160, the Butterfly Spring in column 164, and the Devil's Eyeglass in column 172 (Figures 2 and 3).

The side boundaries of the model are approximately 10 km from the geothermal system, and are closed. Conditions on the lower boundary represent the heat and mass flows at 2250 m below sea level, below the Wairakei system. The top boundary is open to a constant temperature, pressure, and humidity ‘atmosphere’ block that is large enough to absorb flows into and out of the model and remain unchanged. The surface blocks have a mass injection to simulate a constant infiltration of 10 % of the average rainfall.

The model surface represents the ground surface; where overflowing pools occur at Alum Lakes, the top of the model is both the land and phreatic surface.

5 MODEL CALIBRATION

5.1 Introduction

This model is designed as a two-dimensional representation of the entire Wairakei system. Therefore it is calibrated with the available reservoir data (natural state temperature for depth, reservoir production pressure and well enthalpy), as well as the surface data on Alum Lakes, which consists of mass discharge. Water level and chemistry data are available for Alum Lakes but have not been included in this calibration.

As with the three-dimensional model, the initial calibration consisted of matching the steady state data, then using this as the initial condition for a transient simulation of the production period.

5.2 Reservoir data

The natural state temperature for depth profiles are composite profiles using all the available data, from pre-production early production time, for each of the borefields: the Eastern borefield, the Western borefield, and Te Mihi. These are used to calibrate the permeability structure and the location of the deep recharge.

The production history matching uses the reservoir pressure history and well enthalpy from the Eastern Borefield, the Western Borefield, and Te Mihi.

5.3 Alum Lakes data

The Alum Lakes field data is from Gregg (1951) and Bromley, (2001) consists of mass flow measurements from Pirorirori, the Butterfly Spring, and the Devil’s Eyeglass. Flow measurements from the Kiriohineki Stream that drains the Alum Lakes area is not used to calibrate the model.

The natural state data used to calibrate the model consists of the initial mass flow measurements before production began in 1953, and the data from the production period is the continuing record of the outflow from the Alum Lakes features. Unfortunately there is very little flow data from the early production until the mid 1990’s.

6 MODELLING RESULTS

6.1 Reservoir results

The natural state model temperatures (Figure 4) agree with the accepted conceptual model of the Wairakei system of a hot upflow bending and flowing horizontally under the Western and Eastern Borefields to a shallow outflow in the east.

Generally the temperature versus depth profiles for the model are a good match to the interpreted reservoir temperature (Figure 5a), b), and c)). The shallow Western borefield temperatures are slightly cool, but are a good match at reservoir depth (0 to –500 mrsl); the Eastern Borefield and Te Mihi are a good match.

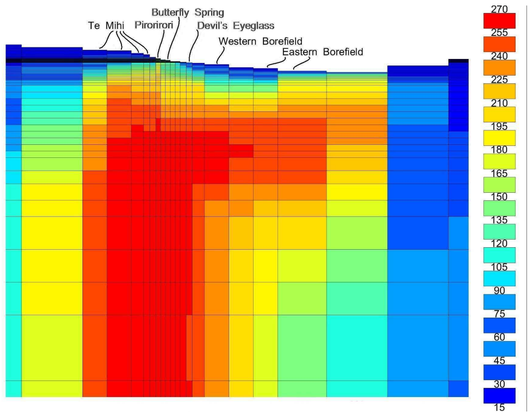
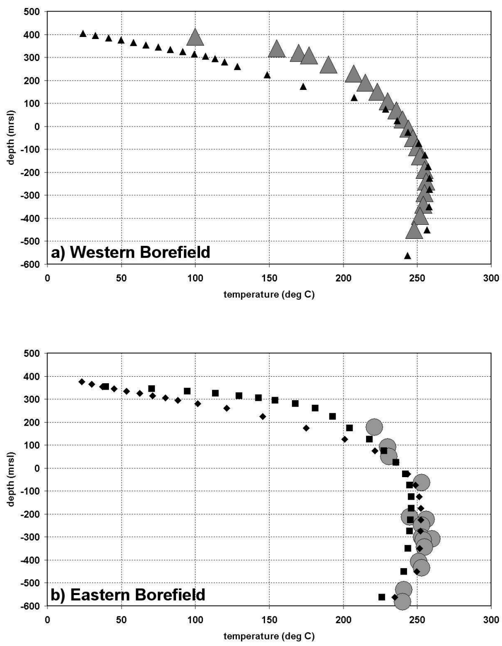


Figure 4. Vertical cross section, natural state model block temperature. This shows the model reservoir and surface above only - the basement and the colder margins to the east and west are clipped from the diagram.



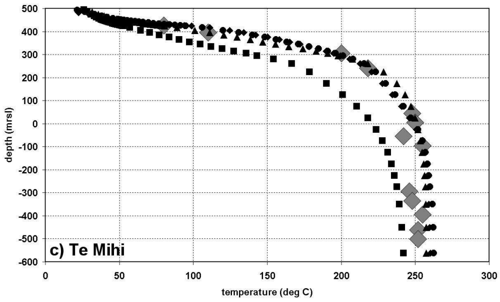


Figure 5. Natural state temperature versus depth for a) Western Borefield, b) Eastern Borefield, and c) Te Mihi. The Te Mihi sector of Wairakei is represented by four columns in the model, hence the temperature versus depth profiles are shown for all four columns

Calibration for the production period uses the well enthalpy and reservoir pressure from the production wells. The results (Figures 6, 7, and 8) are sufficient to establish if there is a response in the surface flows at Alum Lakes. The pressure results for the Western Borefield, and the enthalpy and pressure for the Eastern Borefield are a reasonable match, while the model enthalpy for the Western Borefield and Te Mihi, and the pressure at Te Mihi could be improved.

The 2-D model in this study is based on a large 3-D model of Wairakei. The layer structure for the reservoir was the same as for the 3-D model, but the reservoir permeability structure had to be modified to achieve the this match to reservoir data.

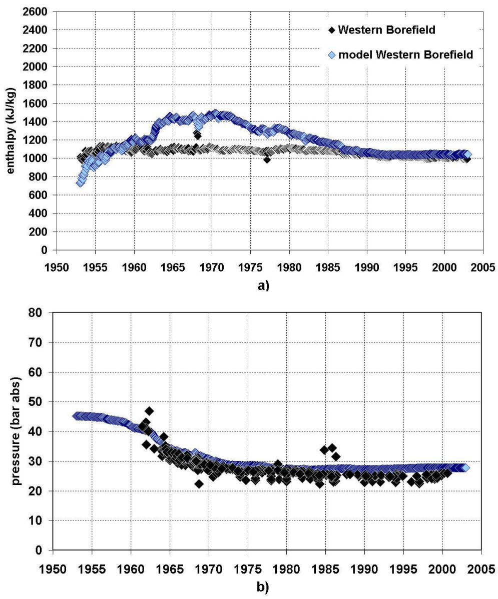


Figure 6. Western Borefield, a) well enthalpy and b) reservoir pressure.

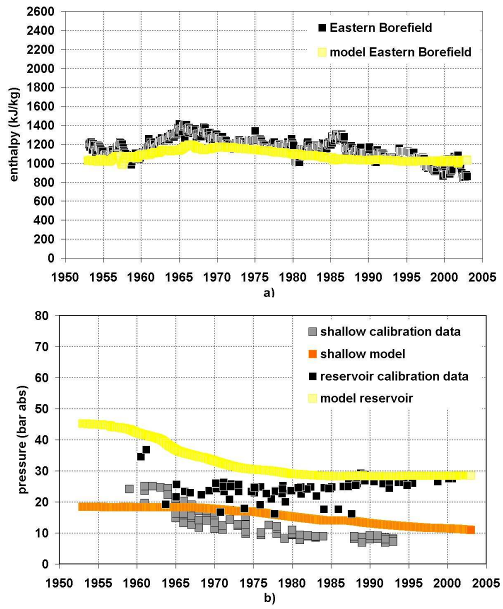


Figure 7. Eastern Borefield, a) well enthalpy and b) reservoir pressure.

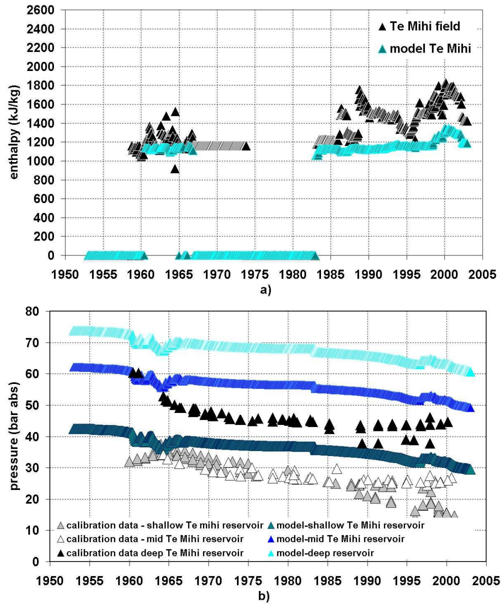


Figure 8. Te Mihi, a) well enthalpy and b) reservoir pressure.

6.2 Alum Lakes Results

Figures 9 to 13 show the liquid and gas flows below the Alum Lakes in the natural state, then in the production period at 1975 and 2003. Each figure is a cross-section through the model Alum Lakes system, with the arrows representing the flow between adjacent model blocks. The length of the arrow represents the mass flow rate, with a scale arrow on the far right of each figure. For the liquid mass flows, the scale arrow represents a flow of 8 kg/s; for the gas mass flow the scale arrow represents 1.6 kg/s.

The natural state liquid flows (Figure 9) show an overall shallow groundwater flow downhill from west to east. There is a strong upflow from the reservoir in column 160, some of which outflows at Pirorirori, with a contribution from the shallow groundwater. The liquid from the Butterfly Spring and the Lower Devil's Eyeglass is a combination of reservoir and groundwater liquid.

In the natural state steam also flows up through the main conduit from the reservoir (Figure 10). The steam condenses in the water below Pirorirori and the Butterfly Spring. There is a downflow of groundwater, reservoir liquid, and condensed steam in columns 162 and 170 that continues to flow downhill and eastwards through the model.

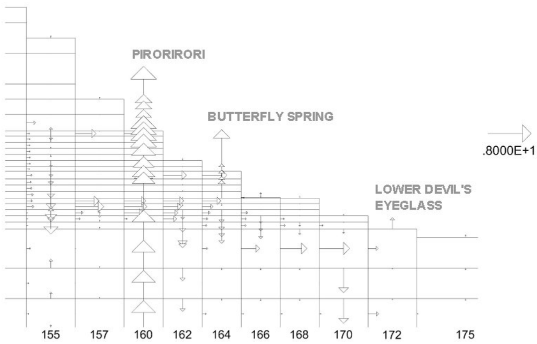


Figure 9. Natural state liquid mass flow between model blocks.

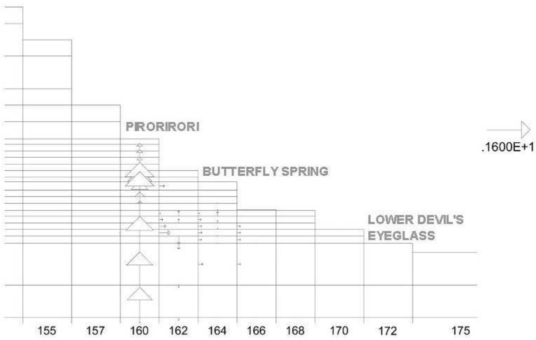


Figure 10. Natural state gas mass flow between model blocks.

By 1975 the liquid upflow from the reservoir (in column 160) has almost ceased, and a downflow of groundwater exists in the shallow layers of column 160 (Figure 11). There appears to be very little reservoir liquid reaching the surface, and the outflow from all the springs is predominantly groundwater. There are strong down flows in columns 162 and 170; these contribute to the deep groundwater flows east across Wairakei. The gas flow in the conduit is greatly reduced (Figure 12), with only a small upflow in the deeper levels of the Alum Lakes system.

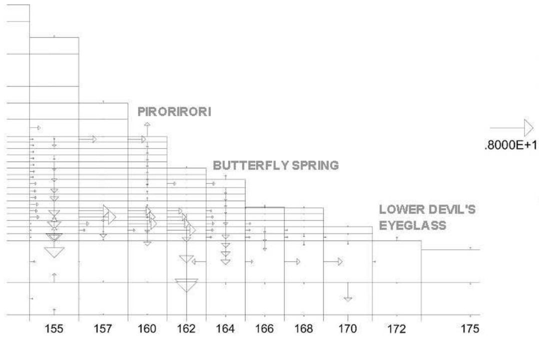


Figure 11. 1975 liquid mass flow between model blocks.

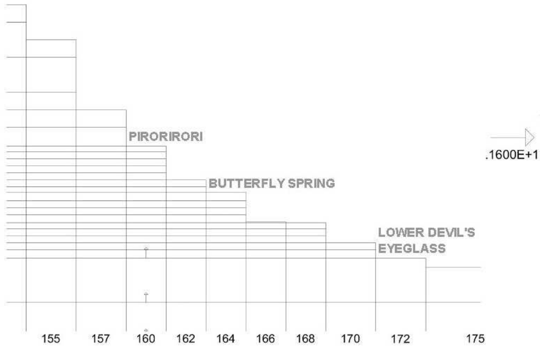


Figure 12. 1975 gas mass flow between model blocks.

Figure 13 shows the liquid mass flow in the same part of the model in 2003. There is a downflow of groundwater into the high permeability conduit to the reservoir, and less groundwater flowing down in columns 162 and 170. There are downflows from the surface in the Pirorirori, and Butterfly Springs blocks, and no flow across the surface of the Devil's Eyeglass. There is no steam in this part of the model.

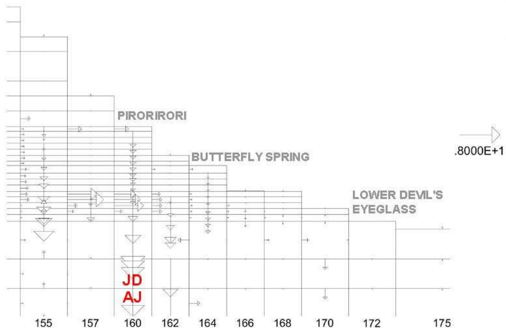


Figure 13. 2003 liquid mass flow between model blocks. Layers JD and AJ are marked in red in column 160. The time history of the water and gas mass flows between blocks AJ160 and JD160 is plotted in Figure 14.

Figure 14 shows the time history of mass flow in the Alum Lakes feeder conduit. In the natural state (1953) there is an upflow of liquid of 10.6

kg/s and gas upflow of 2.5 kg/s in column 160. These flows decrease over time until by early 1975 the liquid flow becomes a downflow and the gas flow ceases altogether. The liquid downflow increases in magnitude until the end of the simulation in 2003, by which time it is flowing at 11.4 kg/s.

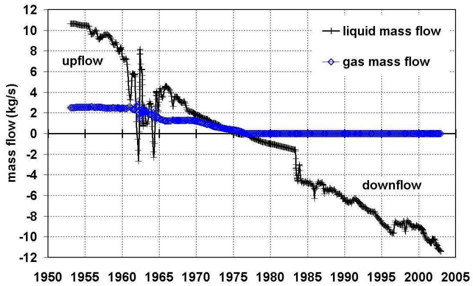


Figure 14. The liquid and gas mass flows in model column 160, the high permeability connection between Alum Lakes and the reservoir. The flows shown are between blocks at 405 masl (layers JD and AJ on Figure 13). The positive mass flows are upflow; the negative mass flows represent downflow.

The flow through the top of the model blocks representing Pirorirori, the Butterfly Spring, and the Devil's Eyeglass is shown in Figure 15. The calibration data from Gregg (1951) and Bromley (2001) is also shown.

The initial flows are a reasonable match to the natural state calibration data and the early (1957) data point for Pirorirori. The Butterfly Spring model flows cease by 1984; there is no record of when the flow actually stopped. The model Pirorirori outflow continues until 2001, although Bromley (2001) notes that Pirorirori may have stopped flowing by the mid 1990s.

The Devil's Eyeglass continued flowing until at least 1997. This was difficult to achieve in the model, and the best result so far has the Devil's Eyeglass flow decreasing from 1965 and ceasing around 1984 at the same time as the Butterfly Spring.

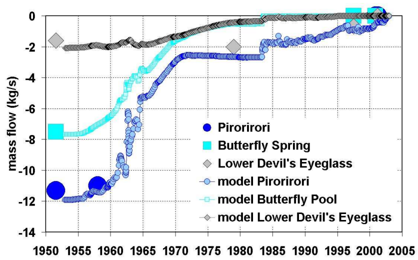


Figure 15. Alum Lakes mass outflow to the atmosphere from 1953 to 2003. Calibration data and model results.

7 DISCUSSION

The 2-D model presented in this study is based on a large 3-D model of Wairakei with finer grid layers in the vicinity of the Alum lakes, and much detail was added to the shallow permeability structure around the Alum Lakes in order to match the calibration data. Using this grid structure the model is able to match the cessation of flows from the Alum Lakes area as a response to pressure decrease in the underlying reservoir. It has been shown that the lakes were fed by an upflow of steam and water from the reservoir through a high permeability conduit, and that the flows from the reservoir decreased over time, with the steam flow and liquid upflow both ceasing around 1975. After this groundwater begins to flow down the high permeability conduit, with the flows increasing in magnitude up to 2003.

8 FUTURE WORK

Some of the reservoir model results could still be improved, namely the enthalpy for the Western Borefield and Te Mihi, and production pressure response for Te Mihi.

Water level data is also available for the Alum Lakes features. The TOUGH2 model described here has the capability to model the declining water levels in the springs once they have stopped flowing, with the important model parameters in this case being the relative permeability and capillary parameters. This is the immediate focus of future work.

9 ACKNOWLEDGMENTS

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