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RESERVOIR PRESSURE DRAWDOWN AND THE ALUM LAKES, WAIRAKEI

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ABSTRACT

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 based on an existing three-dimensional (3-D) computer model of Wairakei system, but uses 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.

INTRODUCTION

The conceptual model of Wairakei postulates an upflow through fractured ignimbrite between Te Mihi and the Alum Lakes, which above –500 mrsl (~1000 m depth) flows horizontally eastwards towards the Eastern Borefield wells and the Waikato River. There is also an upflow of steam from the reservoir that causes the fumaroles and steam heated activity at Karapiti in the southwest, and in the natural state there was a chloride water upflow northeast towards Geyser Valley. In its initial state the Wairakei system was a predominantly liquid reservoir at close to boiling point down to a depth of around 1000 m, with a small volume of steam below the Huka Falls Formation, which forms a low permeability cap to the system.

Production caused pressure drawdown and boiling in the reservoir, and also induced an increase in the deep hot recharge to the system. After 20 years of production the Wairakei system has reached a quasi-steady state, with fluid withdrawal almost matched by hot recharge from the deeper system, the surrounding groundwater, and by the expansion and drying of the steam zone.

The existence of a connection between the surface geothermal activity at Wairakei and the deeper geothermal reservoir was shown by the rapid decline of the activity at Geyser Valley in response to discharge from the production wells in Waiora Valley (Glover and Hunt, 1996). The Karapiti area to the southwest of the Waiora valley also showed a response to production from the reservoir, although this was in terms of increased heat flow from activity such as fumaroles, hydrothermal eruptions and steaming ground (Bromley and Hochstein, 2000). In contrast, the Alum Lakes area at the top of the Waiora Valley is closer to the production wells, yet has shown a slower response to production (Bromley 2001) in that the flow from the Lakes did not cease until the early 1990's. A possible explanation for this is the relatively large proportion of groundwater flowing through the Alum lakes system. In contrast the chemistry of many of the springs at Geyser Valley indicated a high proportion of reservoir fluid

(Glover, 1996, 2000), and activity at the Karapiti area is fed by a strong steam flow from the boiling reservoir, flowing up-dip through the buried Karapiti rhyolite dome.

This study uses a 2-D model of the Wairakei system that is calibrated to three sets of data: the reservoir natural state, the response to production, and the outflow from the Alum lakes and nearby surface features. In the model the Alum Lakes are connected to the reservoir by a high permeability vertical conduit, which in the natural state has an upflow of steam and hot water into the overlying groundwater. As the reservoir pressure decreases, the liquid upflow weakens, the steam upflow ceases, and a downflow of groundwater develops in the conduit.

Description of the 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. In the natural state Alum Lakes water was originally a mixture of steam, a small amount of deep chloride water, and groundwater, (Grange, 1955, Glover, 2000). Ninety-six percent of the springs had a pH of less than 3.7, and of the three remaining springs, two flowed into Pirorirori, the largest lake in the Alum lakes area. Eighty-four percent of the springs were 'turbid' or 'mudpots' (Gregg and Laing (1951), Bromley (2001)).

Bromley (2001) identified some significant features of the area that have experienced reduced spring flows in the last 50 years. In order of descending elevation they are:

<u>Pirorirori:</u> Pirorirori (#403) is the largest individual feature, and the source of the Kiriohineki Stream which drains the area. In 1951 Pirorirori had a temperature of 47 °C, 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 (labeled as #401 and #402 by Gregg and Laing (1951)) with a 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 does not record a zero flow until 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 has ceased flowing.

<u>Butterfly Spring:</u> The Butterfly Spring (Heavenly Twins) originally consisted of two pools {Gregg and Laing, 1951) which 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.

<u>Devil's Eyeglass:</u> The Devil's Eyeglass springs flowed between 1951 and 1997, but the chloride content decreased from 667 mg/kg in 1951 to 154 mg/kg in 1997, and the flow 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.

Conceptual model of the Alum Lakes

The chemistry, and the existence of the Lakes above the Wairakei upflow suggests that there is a connection that allows steam to flow from the geothermal reservoir to the groundwater system, and that the natural state pressure in the connection was adequate to prevent groundwater from flowing down this conduit and into the reservoir.

The groundwater in the upper Waiora Valley flows from the high ground in the west to the east (Bromley, 2001), and in the natural state there is some groundwater discharge at the Alum Lakes. A reduction in the reservoir pressure led to a reduction and then cessation in geothermal upflow to the area, followed by groundwater being re-directed from the Alum Lakes to flow downwards into the reservoir.

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

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). This represents the Alum Lakes area, the Wairakei upflow, the Western and Eastern borefields, and part of the Te Mihi steam reservoir. Figure 1 shows the individual Wairakei wells (circles), and the features of the Alum Lakes area (black triangles) that have been used to calibrate the model. The 2-D model does not include Geyser Valley or Karapiti areas, and the recharge zones to the east and west of the system are not modeled in detail. The 2D model should not be seen as a precise representation of the whole of the slice shown. Instead it should be considered as a 2D approximation of the Wairakei system including the main large-scale reservoir features and incorporating a detailed representation of the Alum Lakes area.

The model extends up to the ground surface and thus includes the unsaturated zone. Therefore the air-water version of TOUGH2 was used.

The model surface represents the ground surface and the top surface of the lakes. The surface conditions are constant temperature, pressure, and humidity. The surface blocks also have a mass injection of cold water to simulate a constant infiltration of 10 % of the average rainfall. 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 values used are a proportion of the deep inflows for the 3D model, selected by calibration of the natural state temperatures.

The two-dimensional model required some refinement of the grid layers used in the 3-D model. The layer structure is the same from the base of the model (-2500 mrsl) to 300 mrsl. The grid in the 2-D model above 300 mrsl is refined into 10 m thick layers and then 2 m thick layers where the surface intersects the upper and middle Alum lakes area, except where these were adjusted to match the original water level of the individual springs (Figure 2). 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. The horizontal grids of both the three-dimensional and two-dimensional models are shown in Figure 3.

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. Details of the grid structure in the vicinity of the Alum lakes are shown in Figure 4.

The permeability structure and permeability values in the basement (from –2500 to –1200 mrsl), and in the recharge zones east and west of the reservoir are the same as the 3-D model. The reservoir permeability values in the 2-D model were adjusted to represent the hot upflow and lateral outflow. Production and the deep inflow were scaled down until the two dimensional model gave similar results to the three dimensional model. The permeability structure very close to the surface near the Alum lakes was modified considerably during the course of calibration.

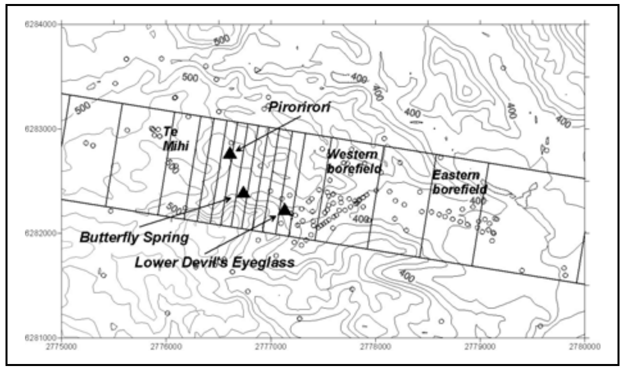

Figure. 1. Detail of the model grid near Alum Lakes showing the Wairakei Borefields

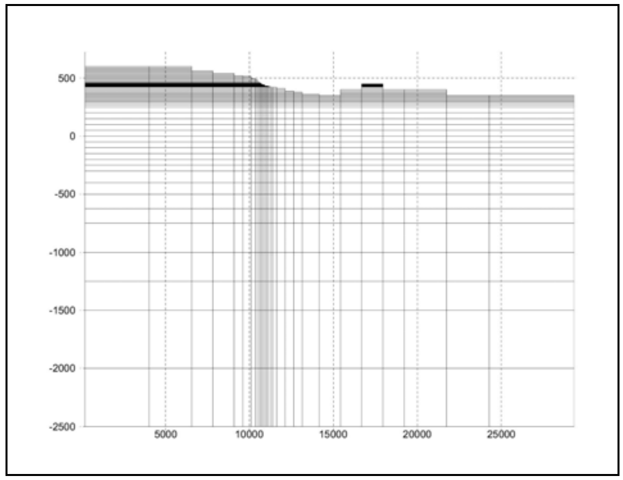

Figure 2. Vertical cross section through the 2-D model.

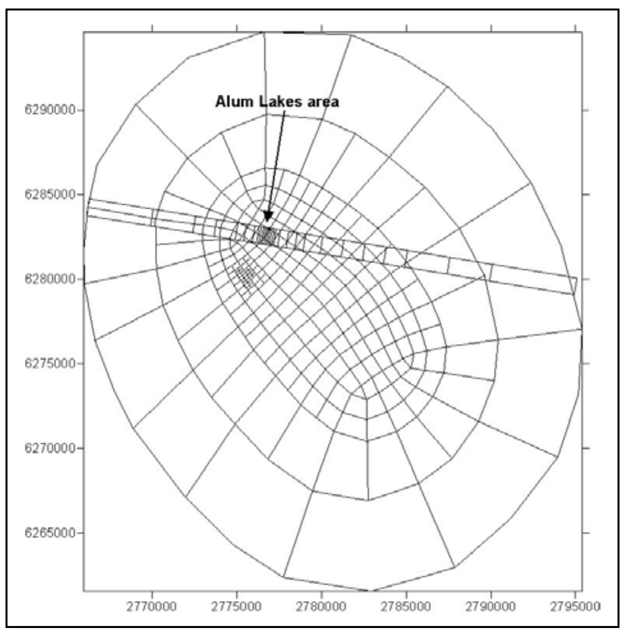

Figure 3. Plan view of the large three-dimensional Wairakei model grid, and the two-dimensional Alum Lakes model grid.

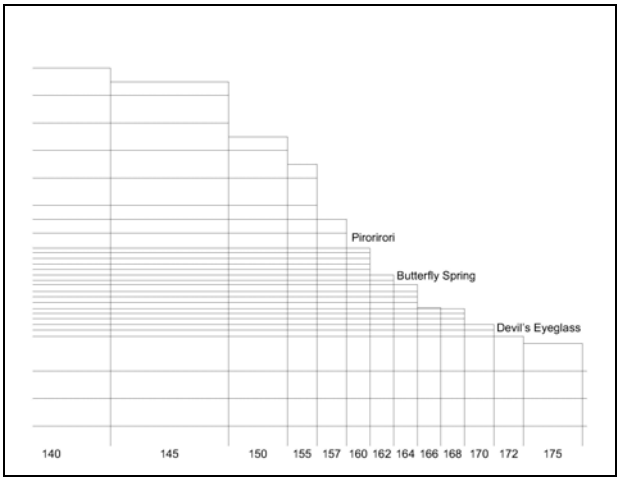

Figure 4. Vertical cross section through the two-dimensional model near the Alum Lakes blocks.

NATURAL STATE MODEL

Reservoir calibration

The natural state temperature profiles are composite profiles using all the available data, from pre-production and early production time, for each of the borefields: the Eastern borefield, the Western borefield, and Te Mihi. The reversals in the Western and Eastern Borefield temperature profiles are due to the location of the wells in a hot outflow, while the Te Mihi wells are closer to the Wairakei upflow.

The model temperatures are matched to the calibration data by adjusting the heat and mass input to the base of the model, and the reservoir permeability structure.

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 too cool, but are a good match at reservoir depth (0 to –500 mrsl); the Eastern Borefield and Te Mihi temperatures are a good match.

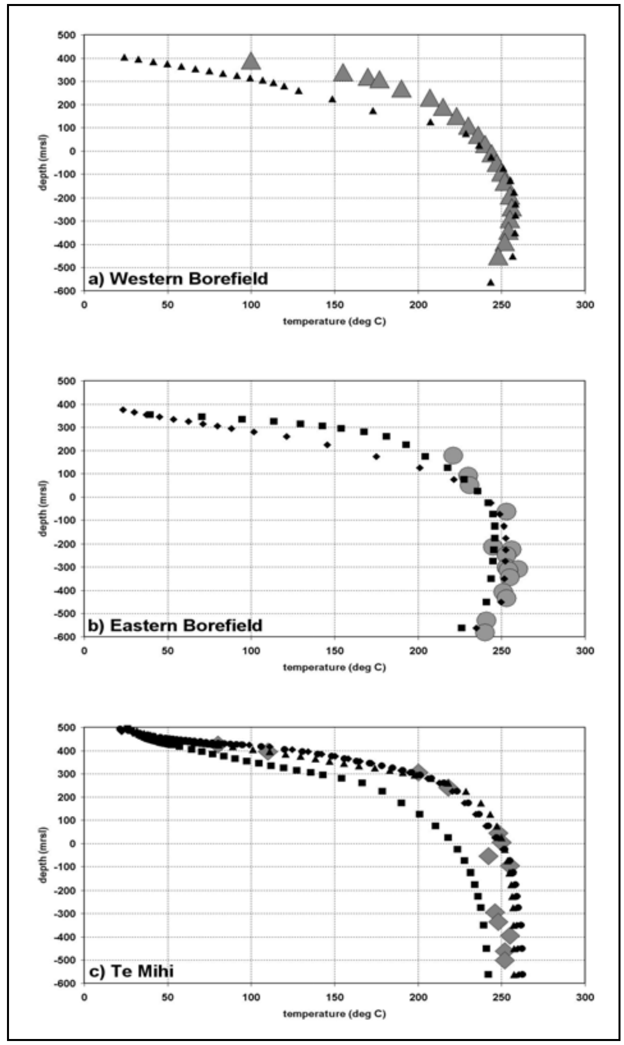

Figure 5. Natural state temperature versus depth profiles for a) the Western Borefield; b) the Eastern Borefield; and c) Te Mihi.

Alum Lakes data

The Alum Lakes field data is from Gregg (1951) and Bromley, (2001), and 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 are not used to calibrate the model. The calibration of the model to match the flow from Alum Lakes consisted of adjusting the shallow permeability structure until the flow from the model surface to the atmosphere matched the discharge data for Pirorirori, the Butterfly Pool, and the Lower Devil's Eyeglass.

The Alum Lakes results are shown below, following the results from the production model.

PRODUCTION MODEL

Reservoir model calibration

The results from the calibrated natural state model were used as the initial conditions for a transient simulation of the production period. Reservoir calibration for the production period uses the well enthalpy and reservoir pressure from the Western Borefield, the Eastern Borefield, and Te Mihi, respectively.

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 the pressure at Te Mihi, could be improved (Figure 6, 7 and 8). The reservoir model is sufficiently accurate to test the response of surface features to changing reservoir conditions.

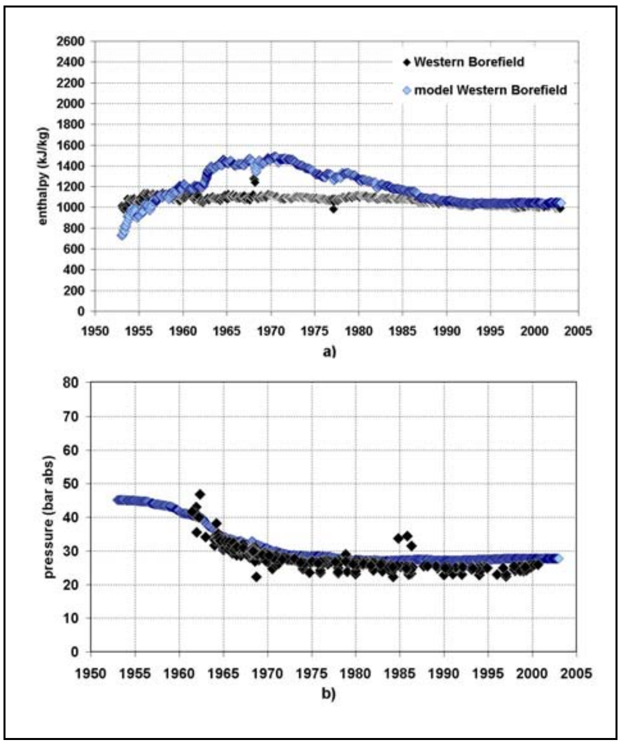

Figure 6. Western Borefield, a) well enthalpy and b) reservoir pressure.

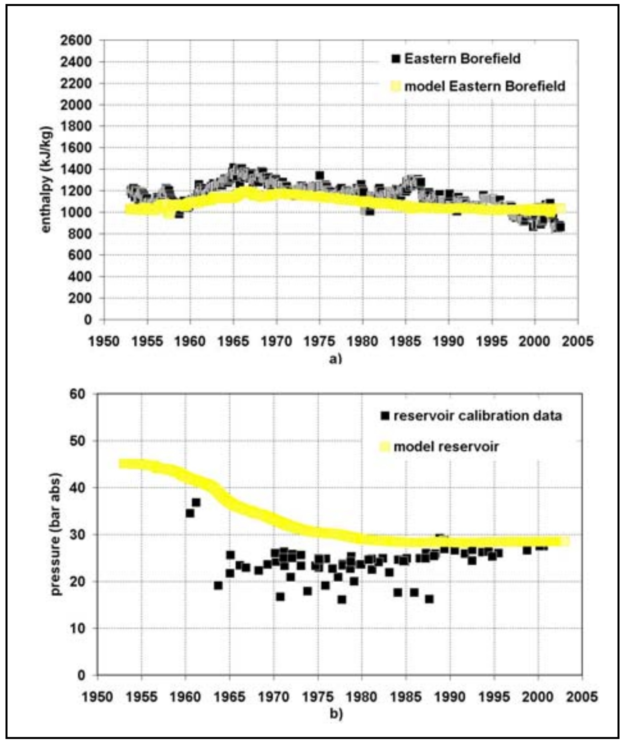

Figure 7. Eastern Borefield, a) well enthalpy and b) reservoir pressure.

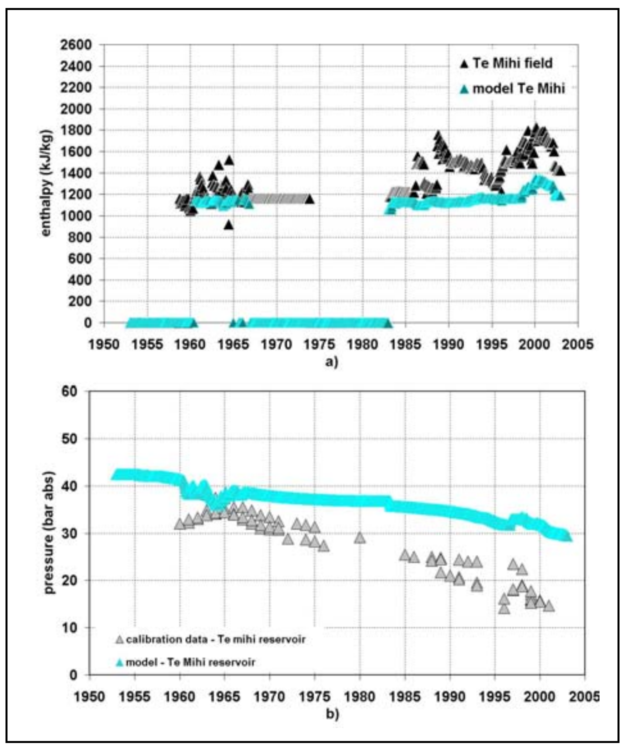

Figure 8. Te Mihi, a) well enthalpy and b) reservoir pressure.

Alum Lakes results

The flow from the Alum lakes is a combination of chloride water, steam heated, groundwater, and cold groundwater. Figures 9 - 13 below show how these flows beneath the Alum lakes change over time. 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. Groundwater that does not discharge at Alum lakes flows downwards in columns 162 and 170, and then east at 40-80 m below the surface. This is not shown on Figure 9 or any following figures because detail is lost as more blocks are shown.

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 liquid, and a small amount of steam, in columns 162 and 170 that flows downhill and eastwards through the model.

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 and 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 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 and east in columns 162 and 170 than in 1975. There are down flows 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.

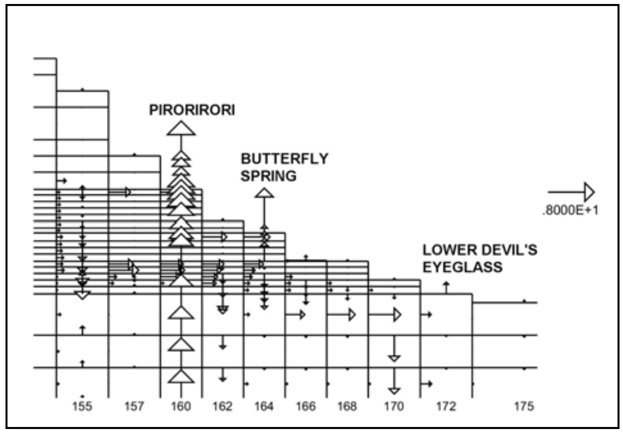

Figure 9. Natural state liquid mass flows between blocks. The scale arrow to the right represents 8 kg/s.

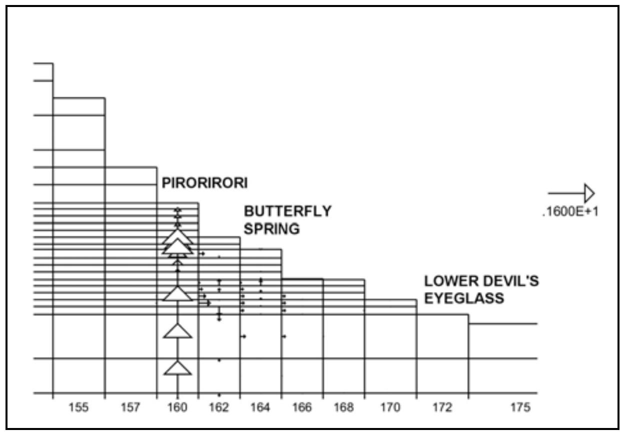

Figure 10. Natural state gas mass flows between blocks. The scale arrow to the right represents 1.6 kg/s.

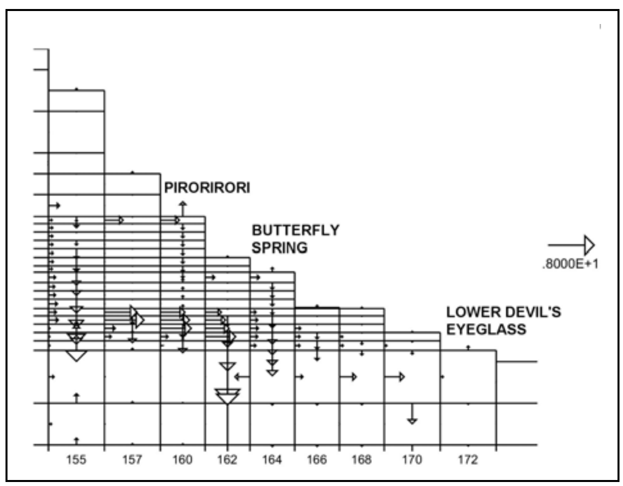

Figure 11. 1975 liquid mass flow between blocks.

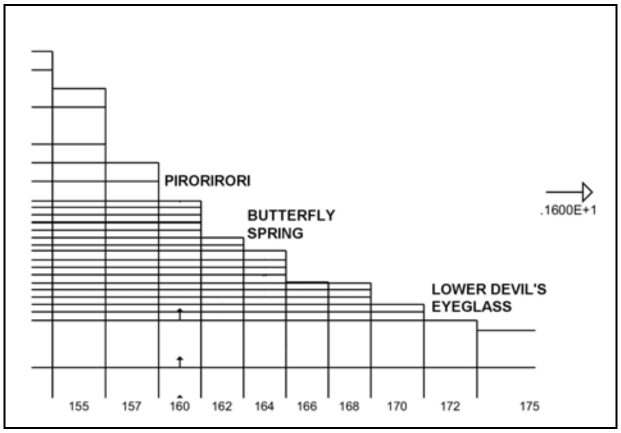

Figure 12. 1975 gas mass flow between blocks.

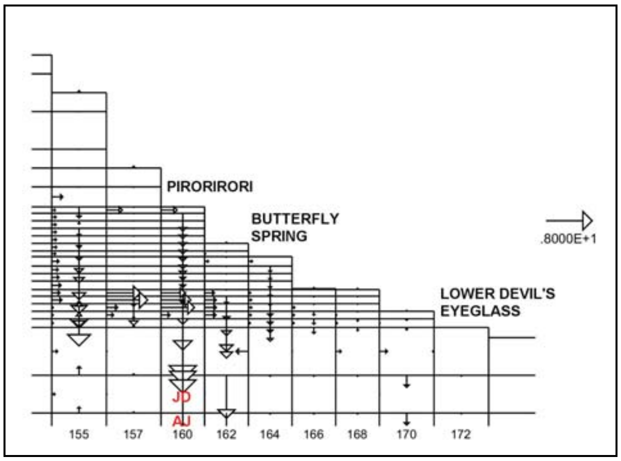

Figure 13. 2003 liquid mass flow between model blocks. Layers JD and AJ are marked in red in column 160. The time history of the water and gas mass flows between blocks AJ160 and JD160 is plotted in Figure 15

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.

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.

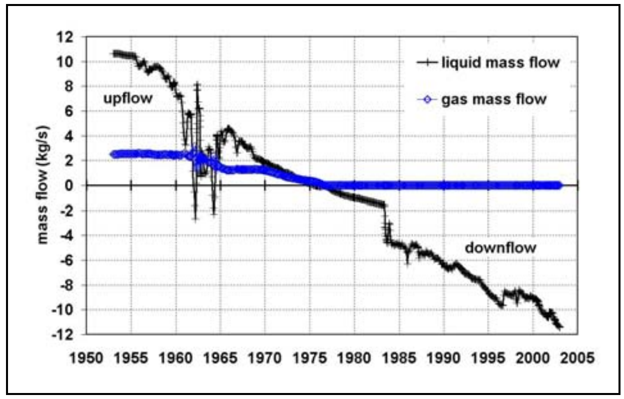

Figure 14. The liquid and gas mass flows in model column 160, the high permeability connection between Alum Lakes and the reservoir. The flows shown are between blocks at 405 masl (layers JD and AJ on Figure 13). The positive mass flows are upflow; the negative mass flows represent downflow.

The 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, but 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 obtained so far has the Devil's Eyeglass flow decreasing from 1965 and ceasing around 1984 at the same time as the Butterfly Spring.

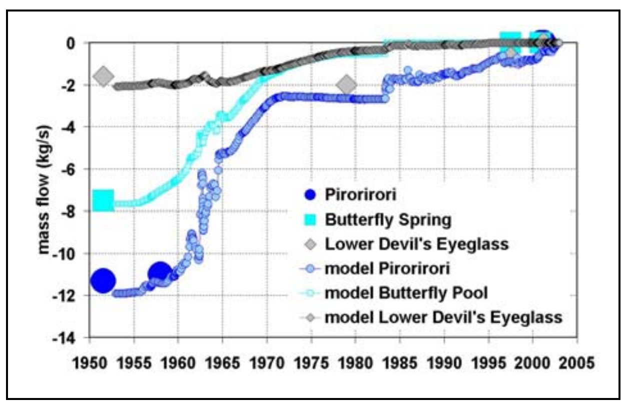

Figure 15. Alum Lakes mass outflow to the atmosphere from 1953 to 2003. Calibration data and model results.

The permeability structure required for the above results is shown in Figure 16. The red column is the high vertical permeability conduit from the reservoir; while the dark blue indicates the low permeability blocks that hold up the groundwater flow and control the surface outflow. The upflow conduit could be interpreted as a fractured zone, while overall pattern of low permeability zones could be due to hydrothermal alteration to clay, or silicified rock. The yellow/green/light blue blocks represent the high permeability pumice volcanic deposits that blanket much of the Taupo Volcanic Zone.

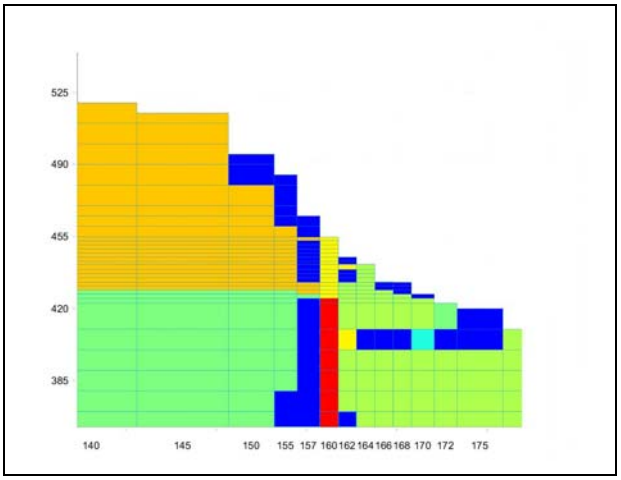

Figure 16. Permeability structure beneath the Alum Lakes.

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,. By linking the reservoir and the surface features, we have shown that the behaviour of the spring flows are a response to reservoir drawdown, although, unlike Geyser Valley which responded to well discharge within a few years, the Alum Lakes springs have taken over 40 years to cease flowing. This is because the lakes were fed by groundwater combined with an upflow of steam and water from the reservoir through a high permeability conduit. Low permeability zones that are possibly hydrothermally altered rock control the shallow subsurface flows. In particular they hold up the eastwards flow of groundwater, allowing some to outflow at the springs, and some to continue flowing downwards and eastwards beneath the Alum Lakes. Flow from the reservoir has decreased over time, with the steam flow and liquid upflow both ceasing around 1975. After this groundwater has been increasingly diverted from the Alum Lakes springs and instead flows down the high permeability conduit into the reservoir, with the flows increasing in magnitude up to 2003. Groundwater that once flowed beneath the Alum lakes is also diverted down into the reservoir.

Chemistry and water level data are also available for the Alum Lakes features. The TOUGH2 model described here has the capability of modelling the chloride content of the lakes, and also the declining water levels in the springs once they have stopped flowing. The next section of work on this model involves modelling the chloride flows in the system, and then the falling water levels in the springs.

ACKNOWLEDGEMENTS

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