Rotorua Geothermal Field: Modelling and Monitoring

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ROTORUA GEOTHERMAL FIELD: MODELLING AND MONITORING

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SUMMARY – The Rotorua Geothermal Field is an area of major geyser activity. The field was subjected to extraction of geothermal fluid by hundreds of households for heating and other purposes from the 1950's. After the decline of some of the thermal features in the mid-80's an extensive monitoring programme was developed to provide an understanding of the system dynamics. The monitoring programme continues through to the current day and includes pressure and temperature monitoring together with the maintenance of a reservoir model. This paper describes recent modelling and analysis of monitoring data undertaken for a review of the Rotorua Geothermal Plan.

1 INTRODUCTION

The Rotorua Geothermal Field has a number of unique characteristics. It underlies a major city, and contains one of New Zealand's last remaining areas of major geyser activity at Whakarewarewa. The geysers are considered to be of regional and national significance, and all the geothermal features have strong social, cultural and economic value. From 1950 to 1986 the field was subjected to a period of intensive fluid withdrawal, during which the field pressures declined along with surface activity.

Concern over the decline of some of the geysers and hot springs at Whakarewarewa led to the establishment of the Rotorua Geothermal Monitoring Programme (RGMP) undertaken by the New Zealand Department of Scientific and Industrial Research and the Ministry of Works and Development. In the winter of 1986, aquifer pressures had fallen to the lowest levels since the monitoring programme began. The monitoring programme recommended to the Government that urgent action was required to prevent further deterioration of geyser activity. As a result, the Government ordered a closure of all wells within a 1.5 km radius of Pohutu Geyser (Figure 1) and introduced a charging regime for extracting geothermal fluid from the field.

The effect of the Bore Closure Programme was an immediate increase in reservoir pressures. This was the result of a reduction of the net withdrawal from around 28,000 tonnes/day in 1985 to 5,500 tonnes/day in 1990.

Environment Bay of Plenty (EBOP) assumed responsibility for managing the field in 1991 under the Resource Management Act. A management plan for the field was developed and the Rotorua Geothermal Regional Plan was made operative in July 1999. The key objective of the plan is to protect and bring about recovery of geothermal surface features while providing allocation for various uses. The plan requires EBOP to undertake monitoring and research to support policy initiatives in the Plan.

2 CONCEPTUAL MODEL

The Rotorua geothermal field encompasses an area of approximately 20 km^2 as defined by temperatures and electrical resistivity measurements and is shown in Figure 1. 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 much greater depths, this has not been verified because no deeper wells have ever been drilled. Hundreds of shallow production wells have been drilled into the upper 300m of the field. A consequence of the preponderance of shallow information is that the modelling and monitoring is focussed on the shallow upper 500m of the reservoir.

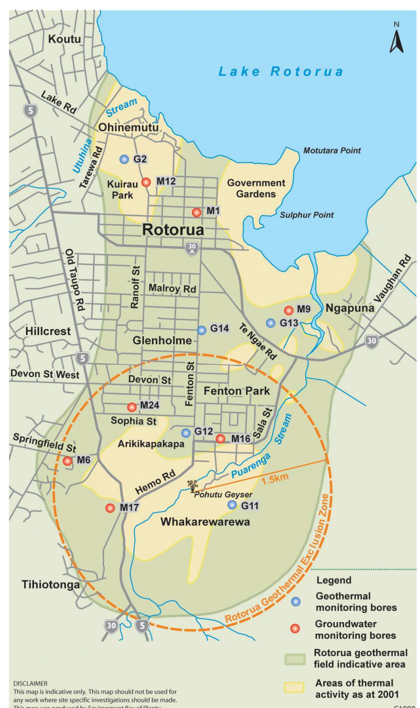

Figure 1: Extent of the Rotorua Geothermal Field, together with areas of surface activity and locations of monitor bores. Supplied by EBOP.

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 two main geological formations that have been identified in the shallow portions of the geothermal system are the Mamaku Ignimbrite and the Rotorua Rhyolite. These two formations comprise the main geothermal aquifer in which production wells are drilled. The rhyolite formations on the western side of the field have been found to be very permeable. These formations are overlayed by sediments that confine the geothermal fluid.

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 (Simpson, 1985). One important fault is the Inner Caldera Boundary Fault (ICBF) in the south of the field. This fault coincides with a sharp reduction in pressure. The inference that has been drawn is that the ICBF is a permeability barrier for north-south flow. Simpson (1985) suggests that other faults may provide enhanced flow paths across the ICBF to the Whakarewarewa area.

There are three main known areas of surface feature activity, at Kuirau Park/Ohinemutu, and Government Gardens/Ngapuna in the north and Whakarewarewa/ Arikikapakapa in the south as shown in Figure 1. 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.

The conceptual model of flow in the system is summarised in Figure 2.

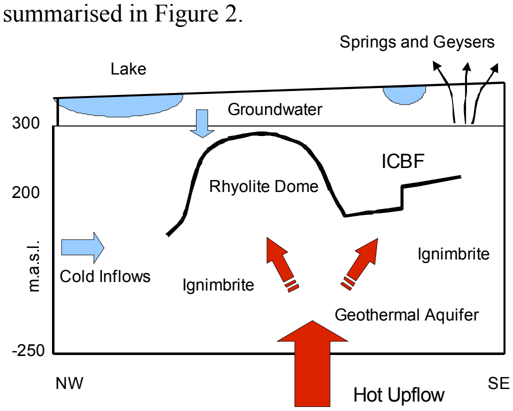

Figure 2: Conceptual model of flow.

3 PRODUCTION ESTIMATES

Estimates of the number of production and reinjection bores and rates have been made by the RGMP and EBOP (RGMP, 1985 and Gordon et al, 2005), and are shown in Figure 3 and Figure 4. The effect of the 1987 Bore Closure Programme can be seen immediately, and over following years net production has gradually reduced to around 1,000 tonnes/day in 2005. In part this is due to requirements in Rotorua Geothermal Plan for full reinjection.

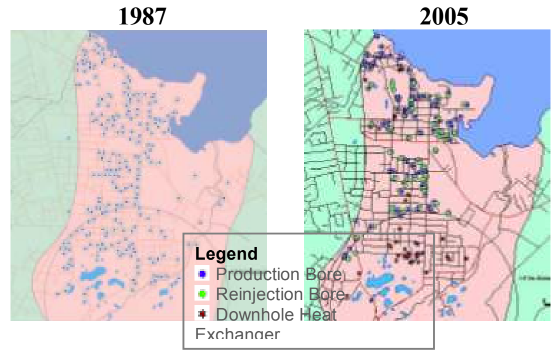

Figure 3: Location of production and reinjection bores in 1987 and 2005. Taken from Gordon et al (2005).

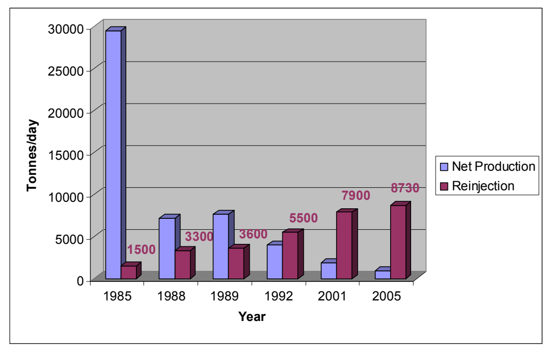

Figure 4: Net production and reinjection rates.

4 PRESSURE AND TEMPERATURE MONITORING

A network of monitoring bores was established in 1982 to record water levels and temperatures in the geothermal aquifer. Monitoring of some of these bores, together with some newer bores, is still undertaken by EBOP. Pressures or water levels are collected from the M-series monitoring bores, which are drilled to depths of 200 to 300m and are shown in Figure 1. Long term records have been collected from M1 and M12 in the northern part of the city and M6, M16 and M17 near Whakarewarewa. Shorter records also exist for other monitor bores in the field. All the recorded data is summarised in various EBOP publications (Gordon et al, 2005 and Kissling, 2005).

Water levels from M6, M9, M12 and M16 are shown in Figure 5. From these graphs, a number of features are immediately apparent:

- Generally water levels were decreasing before the 1987 Bore Closure Programme.
- Between 1986 and 1988 all monitor bores showed significant increases in water levels.
- Further overall increases were seen between 1990 and 1995 in all wells
- M12 and M16 showed further increases from 1995

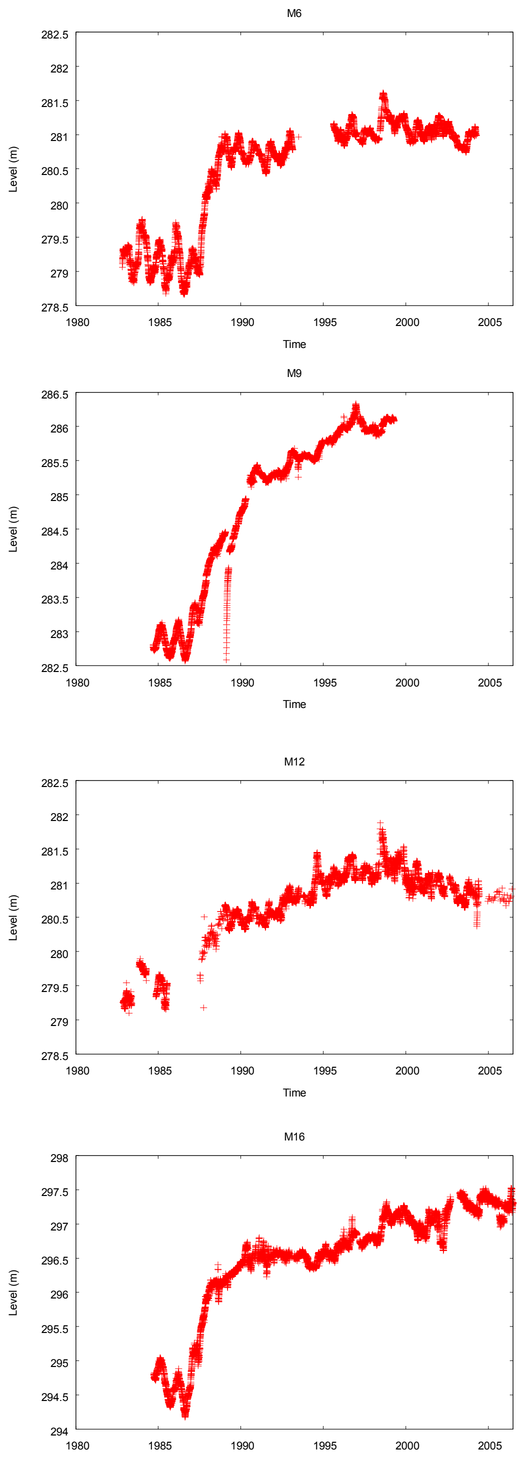

Figure 5: Water levels from monitor wells M6, M9, M12 and M16

5 SURFACE HEAT FLOWS

The surface heat flow from Whakarewarewa is a key indicator of the impact of production from the field. 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 streams. 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.

Grant et al (1985) inferred a heat flow of 300MW in the natural state, corresponding to 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 on 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. Note there is considerable uncertainty in this estimate.

At Kuirau Park, flows had nearly ceased by 1985. After the 1987 Bore Closure Programme a hot overflow (70-80ºC) from the lake of between 600 and 5,180 tonnes/day was observed in 1993.

6 RESERVOIR MODEL

As part of the monitoring programme, various reservoir models have been developed over the years. The current model is described in detail in Burnell (2005). That model was developed for the TOUGH2 simulator (Pruess, 1991), using the EOS7 module (water, air and NACL). 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 the primary focus of the model is predicting changes to the shallow aquifer and surface features, this approximation should suffice.

The model covers the Rotorua Geothermal Field and its surrounds. It is built from 7 horizontal layers that start at the ground surface and extend to a depth of 570m. The grid used in each horizontal layer is shown in Figure 6, and covers the recognised hot shallow aquifer at Rotorua. 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.

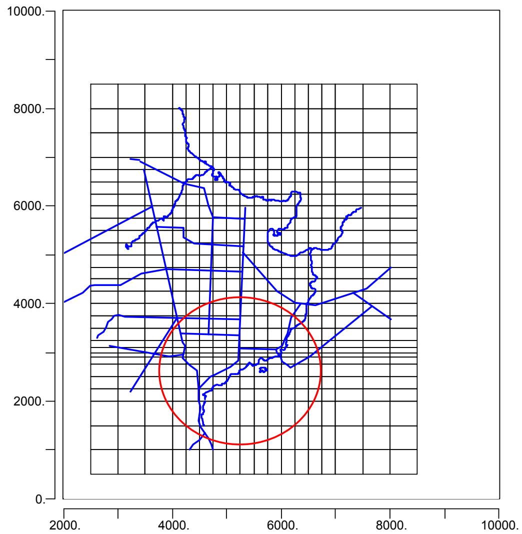

Figure 6: Model grid layout in a horizontal layer. The coordinates refer to map coordinates with (2,000, 0) on the diagram corresponding to (2790000N, 6332000E) in map coordinates. The blue lines are local roads, streams and the lakefront, and the red line approximately shows the 1.5km exclusion zone.

6.1 Boundary Conditions

The model is open along the north and south sides, so 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. The southern boundary pressures are 3 bar higher than those of the northern boundary. Temperatures at both boundaries were cold conditions of 15ºC.

The top surface follows the topography, connecting the model to the atmosphere at 1 bar and 15ºC. The east and west boundaries of the model were closed, as was the bottom of the model except for regions where inflow occurred.

6.2 Inflows and Outflows

The spring and geyser outflows were modelled as wells on deliverability. The flowrate of the outflows were set to be proportional to the difference between the reservoir pressure at a prescribed depth and a prescribed pressure.

Heat and mass inflows were added at the bottom of the model. The inflows were adjusted until the model outflows and temperatures approximately matched those of the natural state. These flow rates were then allowed to increase as pressures in the reservoir declined. The main inflows were sited under Whakarewarewa and along the Puarenga Stream. A further inflow was placed under Pukeroa Dome as the chemistry suggested that there is a separate flow in this region.

In addition to inflows at the bottom of the model, rainfall was also included. In the upper layer 13,800 tonnes/day was injected uniformly over the modelled area. This corresponds to an infiltration rate of about 7.5%.

6.3 Model Calibration

The model was mainly calibrated against changes in the system; primarily because of uncertainty in the natural state data. Specifically, the model results were compared to:

- Pressures from 1985;
- Temperatures in 1985;
- Inferred outflows at Whakarewarewa in the natural state and measurements from 1985;
- Pressure changes from 1985 to 1992;
- Chloride concentrations in 1989;

6.4 Match to Data

6.4.1 <u>Natural State</u>

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.

The model pressures are higher than the inferred values but show a similar pattern, with higher pressures in the south and east and lower pressures at the lake end.

6.4.2 <u>Pre-Closure State</u>

The model was run for 30 years and the model pressures and measured data at 180 m.a.s.l. are shown in Figure 7. The figure shows that the model pressures are too high. However, they do show similar spatial behaviour to the measured pressures, with a pressure high in the southeast, rapidly changing near the ICBF and a pressure low in the north. Further, the modelled changes in pressure since production started are of the right magnitude with declines of about 0.2 bar.

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 (Glover 1992).

The model temperatures provide a reasonable match with the measured temperatures from 1985.

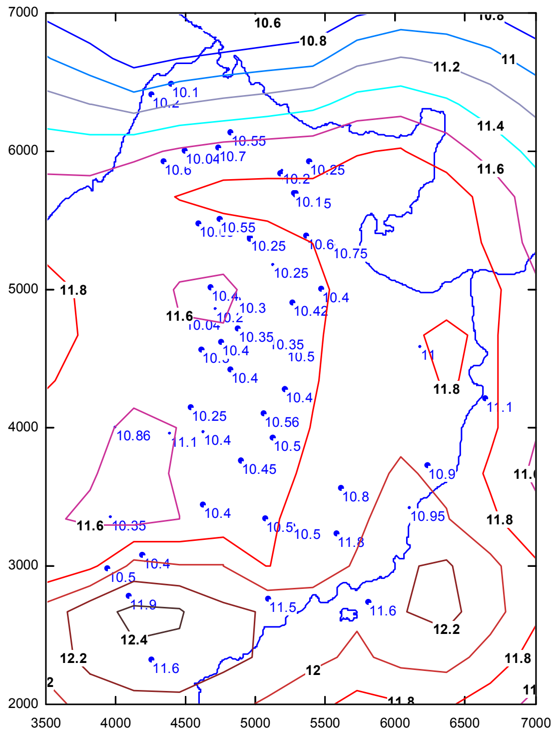

Figure 7: Model pressures from 1985 at 180 m.a.s.l. compared to measured pressures

6.4.3 <u>Response to the 1987 Bore Closure Programme</u>

The model response to the 1987 Bore Closure Programme in 5 monitor wells is shown in Figure 9 to Figure 12. The modelled recovery gives good agreement except for M12, where the model underestimates the recovery after 1995.

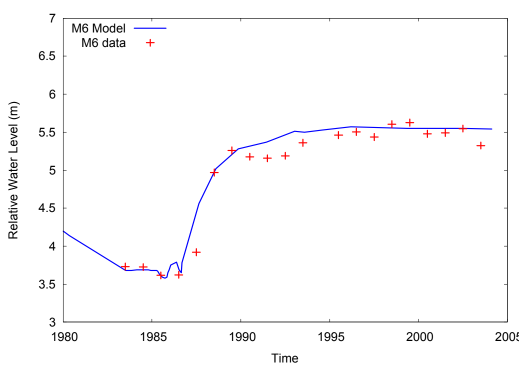

Figure 8: Model water levels at M6

The model heat flow from Whakarewarewa is 245 MW in 1993 which is a reasonable match to the estimate of more than 216 MW in 2000. The modelled mass flow from Kuirau Park of 1,380 tonnes/day of hot reservoir fluid 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.

There is little temperature data after 1986 with which to compare the results.

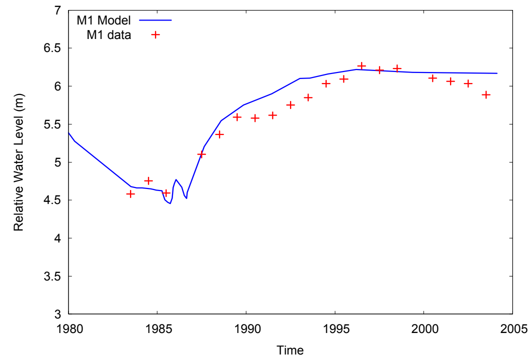

Figure 9: Model water levels at M1

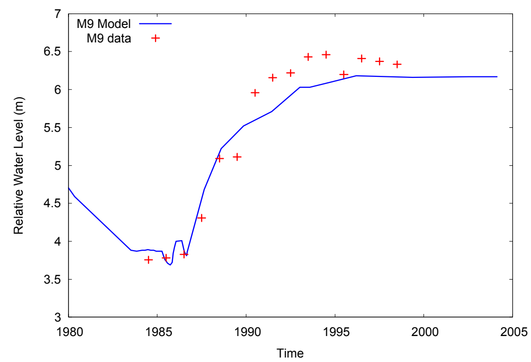

Figure 10: Model water levels at M9

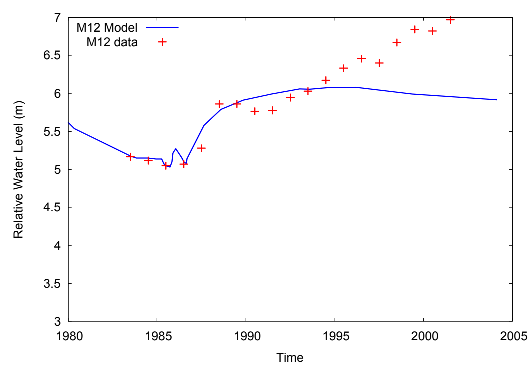

Figure 11: Model water levels at M12

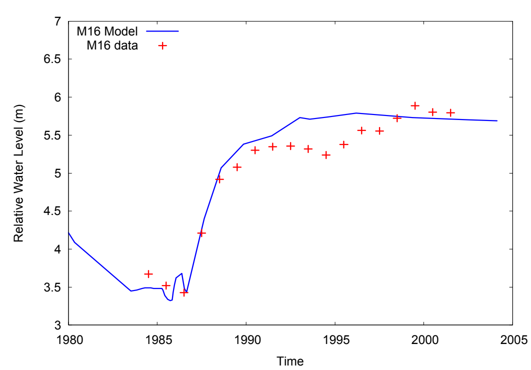

Figure 12: Model water levels at M16

6.5 Seasonal Variation in Production

Prior to the Bore Closure Programme, water levels at Rotorua showed a seasonal variation. 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. The modelled change in water level is compared to the measured values in Table 1.

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

Well	*Measured (m)*	*Modelled (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 detail of the local spatial pattern of withdrawal to estimate these changes. Lack of detail in the spatial pattern will mean that the model pressure changes will be averaged out over larger regions.

7 CONCLUSIONS

Monitoring data from the Rotorua Geothermal Field has been presented, together with a description of a reservoir model of the field. After the 1987 Bore Closure Programme, significant changes occurred in the field: net production in the field reduced from 28,000 tonnes/day in 1985 to 1,000 tonnes/day in 2005. As a consequence of this reduction in production, reservoir pressures have shown a significant recovery.

The reservoir model gives a good match to the changes seen since 1987, although the absolute values of the model pressures are too high.

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