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PRESSURE CHANGES IN ROTORUA GEOTHERMAL AQUIFERS, 1982-90

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Abstract—Pressure measurements made in the shallow geothermal aquifers at Rotorua during 1982-87 show a seasonal pressure cycle caused by seasonal changes in withdrawal and not seen in the overlying cold groundwater aquifers. Pressures rose sharply during the Bore Closure Programme in 1987-88 and subsequently settled in a new steady state with most of the variation caused by rainfall changes. The winter withdrawal before the Bore Closure Programme was about 31 000 tonnes/day, and the summer withdrawal was about 20% less. The Bore Closure Programme reduced winter withdrawal to 11 000 tonnes/day and summer withdrawal was similarly reduced. Reinjection to production depth increased from less than 1000 tonnes/day to about 3500 tonnes/day. The size of the pressure rise during the Bore Closure Programme suggests that only about half the decline in pressure since 1960 can be attributed to withdrawal. A drop in groundwater pressure due to lower rainfall in the 1980s than in the 1960s and early 1970s is the most likely cause of the extra decline in geothermal pressures. All pressure changes in the Rotorua geothermal field are small compared to those in other exploited fields in New Zealand. The maximum estimated pressure drop is 0.5-0.7 bars, or 5-7 metres.

INTRODUCTION

Several springs and geysers in Rotorua ceased flowing during the 1970s. People with knowledge of geothermal systems thought many more springs would fail due to decreased geothermal pressures if the use of geothermal water continued at a high and wasteful level. A counter argument was that the decline in mean annual rainfall during the 1970s was causing the decline in spring activity at Whakarewarewa. The Rotorua Geothermal Monitoring Programme was introduced to observe the situation and concluded in 1985 that geothermal withdrawal was a major factor in the decline of Rotorua springs.

During 1986, the arguments in favour of restriction of well operation strengthened and the New Zealand Government declared that all wells within 1.5 km of Pohutu Geyser and all wells operated by Government departments in Rotorua were to be closed. The dotted circle on Fig. 1 shows the 1.5 km closure zone. Many Government-owned wells were in the north and used for heating Government Offices and several were used for heating in schools. Individual property owners generally also own any wells on their property in Rotorua.

The Ministry of Energy organised and conducted the Bore Closure Programme. Some wells were closed during 1986 and the early part of 1987 but the main thrust of the Bore Closure Programme started in the middle of 1987 and continued until March 1988. A payment system for

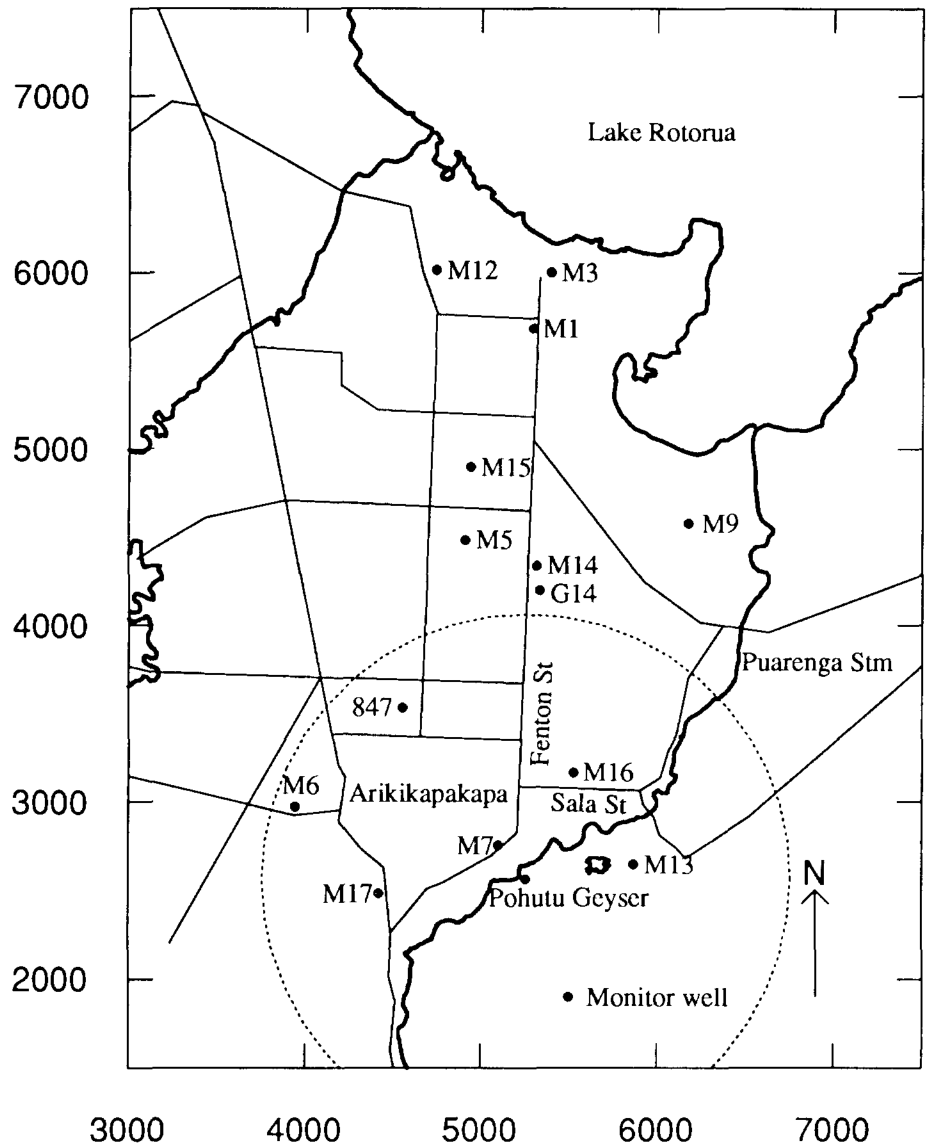

Fig. 1. Map of Rotorua showing the locations of the monitor wells and the groundwater well G14. The dotted circle shows the closure zone 1.5 km from Pohutu Geyser. The axes coordinates are in metres and are relative to the point 2790000,6330000 on the New Zealand mapping grid.

well use was introduced; this encouraged voluntary closures, well sharing, deep reinjection and reduced withdrawal. Consequently, further reductions in withdrawal occurred after March 1988; these changes are not well documented but winter withdrawal reduced to about one third of its 1985 value.

Monitor well network

A geothermal monitor well network was set up at Rotorua in 1982 to measure aquifer pressures using water-level or well-head pressure measurements. These wells tap the geothermal aquifers and are labelled with a number prefixed by *M*. Several shallow groundwater holes were also drilled, labelled with a number prefixed by *G*. Fig. 1 shows the locations of the main geothermal monitor wells (and the groundwater hole G14 used for comparison in this paper).

Originally, the Rotorua Geothermal Monitoring Programme suggested a large number of monitor wells, with some to be custom-built. A smaller number were used and are listed in the Appendix. Only two wells were drilled: M9 at the sewage farm, which is one of the deeper wells in Rotorua and has given good results (although pressures are anomalous in 1989-90), and M7 in the Golf Course carpark. M7 had drilling problems and although it gave good geological data it was never successful as a continuous pressure monitor well and was grouted. With agreement from the owners some disused wells were tested for suitability as monitor wells and introduced into the network. The number of wells used for monitoring has changed over time, and only 6 geothermal monitors remain in 1991. Efforts were made to supplement the monitor wells during the bore closure particularly within the 1.5 km closure zone. Before that, chemical samples and downhole temperature and pressure data were obtained from producing wells.

Pressure changes

During 1982-87, the most notable response in the geothermal monitor well water-level data was a seasonal cycle (Fig. 2). Some well owners were known to regulate their production according to need and so more water was withdrawn during the winter and there was an estimated 20% increase in total drawoff from summer to winter (Boreham, 1985). Increased withdrawal lowers the pressure in an aquifer, causing a corresponding drop in well water level.

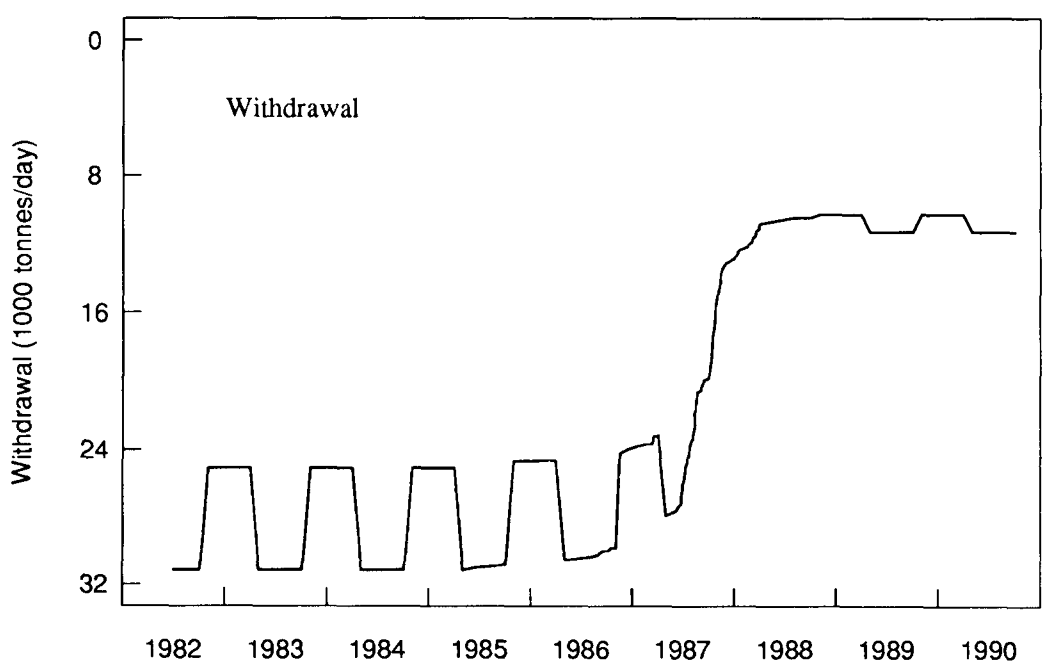

Fig. 2. Estimates of the withdrawal changes during 1986-88, with schematic annual change.

By the end of 1988, the pressures in the Rotorua geothermal production aquifers had almost stabilised at higher values. The effects of the higher pressure took longer to transmit to the springs and geysers, and to other aquifers.

After the bore closure, variations in geothermal monitor well water levels caused by changes in rainfall pattern and changes in water temperature in the well become clearer, as they were no longer masked by the greater variations caused by seasonal withdrawal. Once the initial response to closure occurred there were gradual changes in the monitor well water levels, possibly as other aquifers felt the pressure increase induced by closure.

This paper summarises data on pressure changes in the Rotorua geothermal aquifers and cold groundwater aquifers and concludes that both geothermal withdrawal and decreased rainfall were involved in the decline in geothermal aquifer pressures prior to 1982. More detailed data from the Monitoring Programme are given in Bradford (1990).

Geothermal monitoring in Rotorua takes place in an environment where the overall decisions are political and financial rather than scientific. With the bore closure many bore owners in Rotorua lost the lifestyle which drew them to Rotorua and became angry. The resource management legislation in New Zealand was under review throughout the 1980s and the legal situation was unclear, so opinions differed on what was allowed. Many explanations of how geothermal withdrawal does or does not effect springs were put forth and had to be refuted. People not concerned with monitoring take actions which can change the quality of the monitoring data; I point out some anomalies in the data from such causes.

PRESSURE CHANGES

Various factors that can cause changes in monitor well water levels (or well-head pressures) are listed below. Some of these factors influence the water column in the wells, and are not measures of changes in the geothermal aquifers themselves. Withdrawal in the past may still be causing pressure adjustments.

Natural changes. The supply of geothermal fluid to the shallow geothermal aquifers being tapped at Rotorua is not constant over the long term although it is usually modelled as constant. Natural changes in the deep geothermal source are transmitted to the surface.

Withdrawal changes. Withdrawal changes cause changes in the geothermal aquifer pressure and hence well water levels.

Barometric pressure changes. Barometric pressure changes are mainly transmitted down the well from the surface to the geothermal aquifer. A smaller barometric pressure change is transmitted through the ground above a geothermal aquifer. I have developed methods to remove the barometric response from the surface measurements.

Rainfall pattern changes. Changes in rainfall pattern cause changes in shallow and deeper groundwater levels with aquifer-dependent delay times. These changes are reflected in the G-wells and some (not all) M-wells and seem to be real changes in pressure in the geothermal aquifers. Simple modelling can give an approximate arbitrarily scaled form for the pressure changes caused by rainfall pattern changes.

Long-term rainfall changes. Long-term changes in mean rainfall change the deep groundwater storage. In Rotorua, mean rainfall was high during the 1960s and early 1970s and then declined to the early 1980s when it stabilised at a lower level. The decline in rainfall will have reduced pressures in the groundwater aquifers which surround the geothermal aquifers. That is, the boundary pressure on the geothermal field is reduced.

Temperature changes. The geothermal production aquifers have small temperature changes. Cooling in the cased portions of several geothermal monitor wells since the bore closure has been sufficient to give an under-estimate of the pressure changes in the geothermal aquifers (not specifically corrected for). Temperature changes appear to have been small in the geothermal monitor wells before the bore closure, though they are not well documented.

Boiling changes. Changes in the length of the boiling section have been measured in two geothermal monitor wells. Such changes can markedly alter the surface level and are not easy to predict. Boiling sections in Rotorua wells seem to occur when the aquifers are just two-phase. Small temperature or pressure changes can give large changes in boiling (or not boiling).

Water level data

Data from two representative geothermal monitor wells, M6 and M16, and one groundwater hole, G14, are used for illustration. Figs. 3-5 show the variations in water level for these wells with the barometric pressure response removed. M6 and G14 have been monitored since 1982 and M16 has been monitored since 1984. M6 is in the western part of the geothermal field, M16 in the east and G14 in the centre.

M6 is on Goodwin Avenue and taps an aquifer on the rhyolite. The paper by Wood (1992) in this issue describes the Rotorua geology. M6 was drilled in 1977 to 256 metres and cased to 122 metres, but never produced. Its temperature maximum is about 110°C at around 110 metres depth. The casing was perforated at the temperature maximum when M6 became a monitor well to give access to this hot aquifer. The water-level changes in M6 are typical of the changes seen throughout the central and western parts of the Rotorua geothermal field north of Arikikapakapa (see Fig. 1). Wells in the north such as M12 at the Rotorua Public Hospital show a smaller response to withdrawal but are otherwise similar.

M16 is about 0.6 km from Pohutu Geyser and was a production well in Sala Street. It became a geothermal monitor well in 1984. M16 taps an aquifer on the ignimbrite (see Wood, 1992). It was drilled in 1971 to 153 metres and later deepened. M16 has a boiling section. The level changes in M16 are typical of changes seen in the eastern part of the Rotorua geothermal field .

G14 is in the central area of the Rotorua geothermal field and is close to the bore-closure boundary (1.5 km from Pohutu Geyser). G14 was drilled to 10 metres; the water temperature was 25-30°C in 1982-83 and 40-50°C since 1989 (with no measurements in between).

Monitor wells M6 and M16

Before the bore closure in 1987, M6 (Fig. 3) showed a seasonal cycle with some summer peaks higher than others. Overall withdrawal increased during the winter giving the lower winter water levels. The two higher summer peaks coincide with periods of higher rainfall (as evidenced by water-level rises in G14). The water level in M6 declined in autumn and early winter until the lower evaporation rates and winter rains replenished groundwater storage, usually in June or July. Hence water levels began to rise before the coldest winter months when withdrawal was greatest.

Voluntary bore closure started somewhat before the 1987 winter so the M6 water level did not drop as much that year. Its water level rose sharply when the main thrust of the bore closure started in mid-1987. M6 water level continued to rise during 1988 after the official end of the Bore Closure Programme in March 1988. There were probably some further closures after March 1988 and some changes in bore use, mainly a trend towards re-injection of spent well water to production depths rather than to the shallow groundwater. Some of the pressure rise in 1988 was also caused by rainfall, and much of the pressure variation since is rainfall-induced.

The top of the M6 water column has cooled slightly since 1987 (see Fig. 7). This cooling probably resulted when spent well water was no longer reinjected at shallow levels. Cooling may come from shallow heat withdrawal as M6 is close to many shallow wells with downhole heat

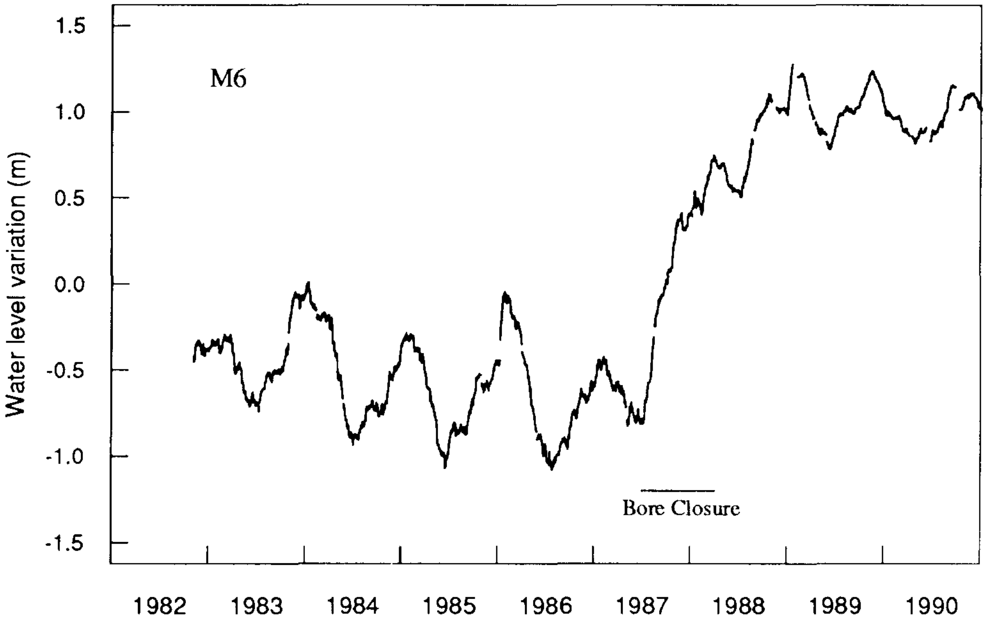

Fig. 3. Water-level variation of M6 with barometric pressure removed, 1982-90.

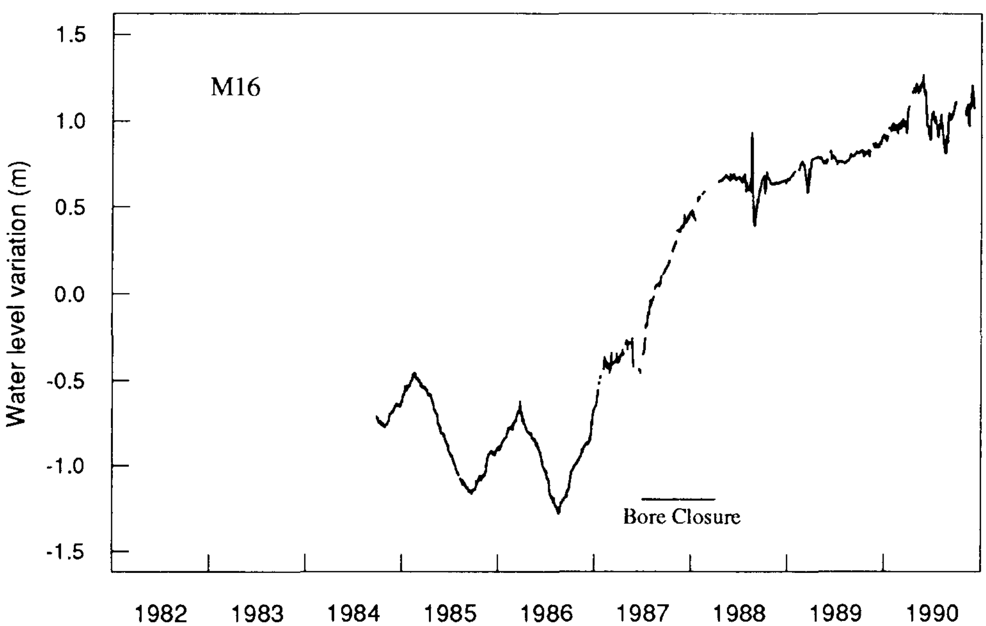

Fig. 4. Water-level variation of M16 with barometric pressure removed, 1982-90.

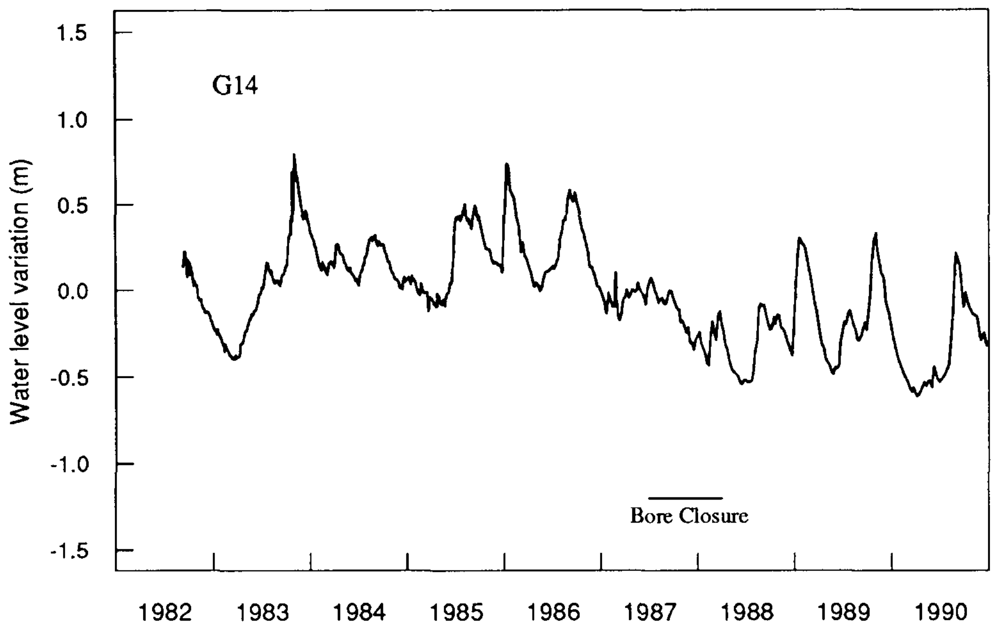

Fig. 5. Water-level variation of the groundwater hole G14, 1982-90.

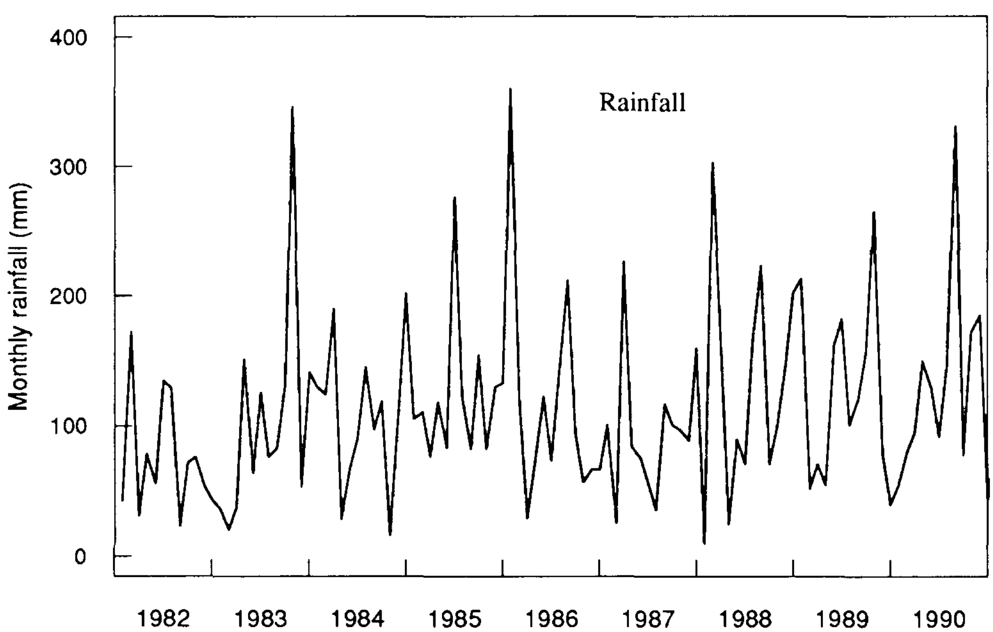

Fig. 6. Monthly rainfall at Rotorua, 1982-90.

exchangers. These wells were drilled after 1987. The cooling-induced water-level change is small compared to the total water-level changes in M6.

Before 1987 there may have been a trend of successively lower winter minima in several geothermal monitor well levels. This may be attributed both to declining pressure in groundwater aquifers and a suspected increase in withdrawal.

Fig. 4 shows the data from M16. The level variations appear different from those of M6 in some respects. The main difference is the lack of any obvious response to rainfall, both before and after bore closure. Before the bore closure, the winter minima in M16 occur later in the year than in M6 but probably give a better estimate of the time of greatest geothermal withdrawal, as they occur in the coldest months and there is no rise after winter rain.

An almost immediate response to the closure of two nearby large bores in June 1987 was seen at M16 suggesting high permeabilities in the eastern aquifers. However, overall response rates to the bore closure are slower in M16 than in M6, indicating either two-phase effects near M16 or even higher permeabilities in the western aquifers and faster transmission times. The water level in M16 started to rise sharply at the end of June 1987, about a fortnight before M6 started to rise sharply. Well closure had moved closer to M6 by the time that M6 started to respond dramatically and it is not clear whether its water level did not respond to the closures in the east or whether there was a delayed response. The overall water-level rise during the bore closure is similar in M16 and M6 and large compared to the seasonal change.

Fluctuations in water level in M16 following bore closure are caused in part by changes in nearby wells. The accidental discharge of a nearby shallow well caused the curious feature on the M16 record in August and September 1988. An aquifer close to boiling exists at about 50 m depth around M16 (Fig. 8) and the shallow well established connection with this aquifer, and explosive discharge followed. Quenching of the shallow well caused cooling in the 50 m aquifer. Temperatures around M16 took some time to re-stabilise and the water level to return to its proper value. The drop and rise in March 1989 is unexplained. The rise and fall in March-April 1990 coincides with a long period of quenching of a deep nearby well. Temperature profiles measured in February 1989 and March 1990 accessed nearly 30 metres more than previous measurements.

Shallow groundwater hole G14

The shallow groundwater gives an indication of how rainfall pattern changes are transmitted to the cold groundwater aquifers. Comparing the variation in time of the geothermal monitor well level data and the groundwater data can help show when geothermal changes are caused by rainfall and when the causes are different.

Rainfall in the 9 months to March 1983 was extremely low and led to abnormally deep minima in groundwater levels in Rotorua. G14 shows this deep minimum in March 1983 (Fig. 5). However, the water level in G14 has reached lower values since the bore closure and the base level may still be declining in 1990. A similar decline is seen in the other centrally located shallow groundwater hole, near Fenton Street at the northern end of the Arikikapakapa Thermal Reserve. The decline in these shallow groundwater levels is probably caused by the lack of return of spent bore water to shallow depths; it is not seen in shallow Rotorua wells in areas far outside the closure zone 1.5 km from Pohutu. Before the bore closure, most of the withdrawn water was returned to shallow soak holes throughout Rotorua. Temperatures in G14 rose about 25°C between 1982-83 and 1989; less hot water entering the aquifers should have led to cooling. Water chemistry suggests the G14 water was steam heated in 1989 (Glover, private communication) and so other aquifer disturbances are occurring.

Rotorua rainfall, 1982-1990

A brief summary of the mean and extreme rainfalls at Rotorua Airport (the official

Meteorological Office station) during the Monitoring Programme follows. The mean annual rainfall 1982-89 of 1348 mm is about 100 mm below the 1964-89 annual mean. 1982 was the driest year and 1988 the wettest year in the period. Months with rainfall above 300 mm were October 1983, January 1986, February 1988 and August 1990. The three driest months were October 1984, February 1987 and January 1988. The months from July 1982 to March 1983 had below average rainfall; the total was 365 mm or 38% of the mean for this period of the year. The months from April to November 1987 also all had below average rainfall; the total was 656 mm or 76% of the mean for this period of the year. Fig. 6 shows the monthly total rainfall in Rotorua from 1982-90.

The dry period in 1982-83 led to a low in groundwater storage which is the most extreme feature of the Rotorua groundwater data from 1982-90. The high rainfalls in October 1983 and January 1986 led to high summer levels in the groundwater. High rainfall in late December 1988 and January 1989 produced a similar groundwater rise. High rainfall in February 1988 followed a long period of mainly dry weather and only gave a moderate replenishment of the groundwater.

Relation between geothermal and shallow groundwater, 1982-1990

The water levels in some Rotorua geothermal monitor wells consistently rise after heavy rain just as the shallow groundwater levels do. The rates of rise and fall of peaks after rainfall are different in the measured groundwater holes and the geothermal monitor wells. Relating the two in a statistically meaningful way is difficult. Rain does not seem to pass straight to the geothermal aquifers in any quantity so a pressure change is transmitted. I do not know the mechanism of transmitting the rainfall signal to these geothermal aquifers, though I suspect good hydrological contact between the meteoric groundwater and the hot geothermal aquifers at a given depth. Horizontal permeabilities are high in the geothermal aquifers and probably also in the meteoric groundwater aquifers outside the geothermal region.

I developed a simple tank model to produce simulated induced changes in the geothermal aquifers (Bradford 1989, 1990). The model smooths the rainfall to give an output which looks like a groundwater level. Rain can only contribute to the output after it has fallen (this is not true of all smoothing procedures) and some account is taken of the current state of dryness and changing evaporation rates. The model contains arbitrary parameters which I have adjusted until the output looks about right and still contains an arbitrary overall scale parameter. The model output continues to look like the M6 water-level variation, say, without further parameter adjustment.

Comparison of Fig. 3 and 5 shows that the high summer peaks in 1983-84 and 1985-86 correspond to times of high groundwater. The low summer geothermal monitor well water levels in 1982-83 correspond to the time of lowest groundwater levels.

There were no extremes of rainfall during most of the bore closure and so there is little influence of rainfall on the water-level rise seen then. However, there have been several extreme rainfalls since, including some in early 1988 during the last three months of the bore closure. Since 1988 much, but not all, of the variation in water level in M6 can be related to changes in rainfall pattern.

The Bore Closure Programme led to a rise in water level in the monitor wells tapping the deeper confined geothermal aquifers and a decline in level in some unconfined shallow groundwater aquifers. Different responses in different aquifers suggest little vertical connection between the shallow groundwater aquifers and the deeper geothermal aquifers, that is, low vertical permeability.

Increases in flow from the cold Utuhina Spring (at the rock face) during 1988-89 suggest increases in pressure in the deep groundwater aquifer which feeds this spring. This deep groundwater aquifer may be in pressure contact with the geothermal aquifers (probably those near M6) and be reacting to the increased geothermal pressures.

Barometric response in geothermal monitor wells

The response to diurnal barometric changes seen on the geothermal monitor well water levels is best considered as noise and removed. However, extremes of barometric pressure (including rapid rates of change of barometric pressure) seem to be capable of triggering changes in the geothermal aquifers. Barometric pressure-induced changes are more likely to occur in aquifers containing two-phase fluid (water and steam). Large changes can be induced by suddenly stopping or starting boiling as there are large volume changes when steam forms or condenses. The winter of 1986 had several extreme barometric events.

Removal of barometric pressure response

The monitor well levels are highly autoregressive, that is, the present values are mainly determined by the previous values, as is the nature of most physical data measured over time. This autoregression must be taken into account when removing the barometric response. Simply regressing the monitor well level against the barometric pressure gives a coefficient of the wrong sign and of the wrong size. Simple linear regression picks up mainly the low-frequency component (the seasonal cycle) rather than the high-frequency day-to-day changes.

I have developed an accurate non-linear regression technique to remove the barometric response (Bradford 1986, 1990). The important features of the technique are taking account of the autoregression, culling of bad data, and the use of procedures to reduce harmful effects of points outside the range of the bulk of the data. An appropriate number of lagged barometric terms are included in the regression. The plots have gaps when I have removed data points. If possible, compatible data sets should be used in the regressions. Since April 1984 I have used daily average values of the monitor well data and the barometric pressure data; before April 1984, I used 9 am barometric pressure data for the M6 regression (as this was the best available).

In April 1984, the Monitoring Programme began recording barometric pressure for its own use. Before that, barometric data came from the Meteorological Station at Rotorua Airport where the barometric pressure is recorded on a chart and the data converted to sea level is stored.

For some of the shorter data series, I difference both data sets before calculating the barometric coefficients by simple regression. Differencing means creating a new series by subtracting the value at the previous time from the current value. This removes the bulk of the autoregression. When the daily average barometric pressure values are not available, I use barometric pressure at 9 am and daily average monitor well levels. The results are less accurate.

The coefficients used in the removal of the barometric pressure can give some information on the nature of the fluid in the well water column and the feeding aquifer. The unlagged change in barometric pressure is negatively correlated with the change in the monitor well levels; some lagged terms of barometric pressure are positively correlated with well level change. The barometric coefficients are highest when the fluids encountered are most compressible, which can be roughly translated to hottest.

Temperature changes

Figs. 7 and 8 show temperature profiles in M6 and M16. Two temperature profiles are shown, one early in the Bore Closure Programme and one from 1990. The dashed line is the boiling point for depth curve. The date of measurement is given. Note that the water level in M16 is above ground and that in M6 is about 30 m below ground. The shallowest measured temperature is at a depth close to the water surface.

Both these wells show cooling at shallow depths. Temperatures in M6 do not reach high values. M16 has one of the more complicated temperature profiles from Rotorua wells with a hot layer at about 50 m depth, then a cooler region before temperatures rise to boiling at about 90 m

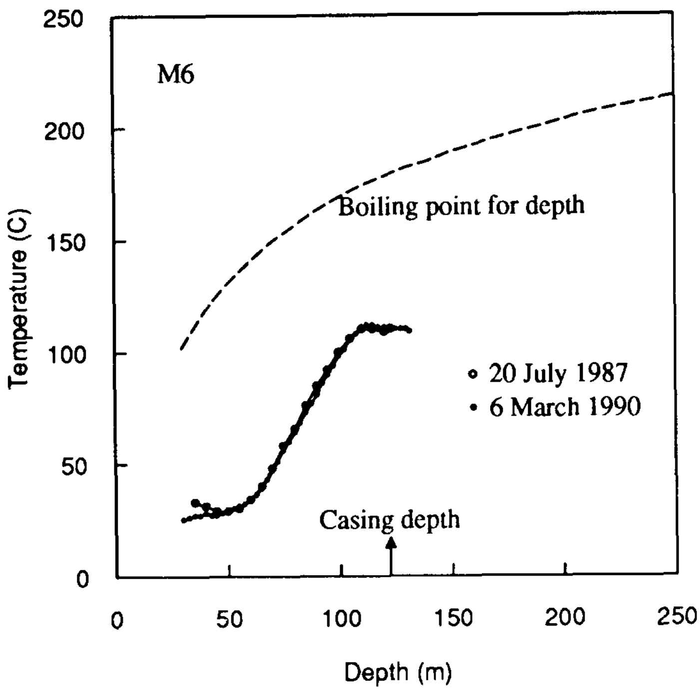

Fig. 7. Temperature profiles in M6 measured in 1987 and 1990.

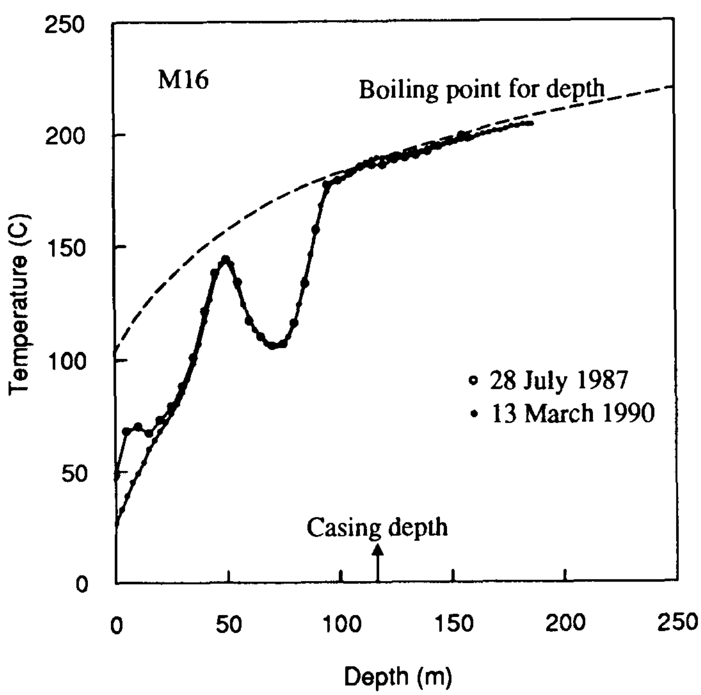

Fig. 8. Temperature profiles in M16 measured in 1987 and 1990.

depth. Except for cooling in the upper portion (and temporary interference) the whole M16 temperature profile, including the boiling section, has stayed almost constant for several years.

The aquifer pressure supports a given weight of water in a well. If the temperature in the well's water column changes, the water density changes and the length of the water column changes and hence water level. Temperature changes must be substantial or must extend over a large depth range to create a water-level change which exceeds other measurement errors. However, cooling in shallow aquifers and boiling changes in some wells can make water-level changes a poor estimator of pressure changes at depth.

Temperatures profiles in the monitor wells were measured prior to instrumenting the wells, but were not measured on a regular basis until the bore closure. However, the available data suggest that any temperature changes were small before then. The importance of accurate temperature profiles has been realised and many were measured during the bore closure as production wells were closed. Monitor well temperature profiles have been measured more often since then.

Cooling of the water temperatures in the shallow parts of other geothermal monitor wells has occurred since the bore closure. Continuing changes, sometimes local, in the shallow aquifers (to about 30 metres depth) are only partially explained and are of concern in the city area. Some cooling would come from the lack of return of warm spent bore water. Also, the hot discharging wells would have provided heat sources for the surrounding country and most of these are no longer present. Heat is now being withdrawn from shallow depths by down-hole heat exchangers and shallow pumped wells.

Summer of 1986-87

The water levels in monitor wells in the north and west of the Rotorua geothermal field were relatively low during the 1986-87 summer (Fig. 3). In some cases, water levels were at their lowest recorded summer values. However, levels in M16 and M9 in the east both reached higher values in the 1986-87 summer than before (Fig. 4). M16 and M9 are probably in close pressure contact with the Roto-a-Tamaheke area of Whakarewarewa where the Ororea group of springs came back to boiling overflow in the 1986-87 summer. Water levels have not been recorded for long enough to know how unusual the high values in the 1986-87 summer are. None of the causes suggested below for the higher pressure and return of flow seems capable of giving a large enough pressure change.

The Bore Closure Programme had been announced but was not operational in the summer of 1986-87. However, there were some unusual changes in net withdrawal. A large well between M9 and M16 stopped production on 31 August 1986, apparently after the collapse of the uncased section of the well during a small earthquake. A second well (by the Puarenga Stream near M16) with a broken casing was partially grouted from September 1986 to March 1987. The broken casing allowed cold water to enter the geothermal aquifers via a fissure, struck while drilling, at a variable rate between 1 and 4 litres/second from mid-December 1986 to the end of March 1987. Another possible cause of the pressure increase is a re-direction of underground flow between different fissures as a result of seismic activity.

WITHDRAWAL CHANGES

The Rotorua Geothermal Task Force made estimates of summer and winter withdrawal for all bores in use in 1985 (Boreham, 1985). The estimated total winter drawoff was approximately 31 000 tonnes/day and the estimated total summer drawoff was approximately 2[illegible] 000 tonnes/day (see Fig. 2). Siitonen (1988) and Timpany (1990) made similar estimates of withdrawal after the bore closure. The winter withdrawal had become about 11 000 tonnes/day, the summer withdrawal about 10 000 tonnes/day and about 3500 tonnes/day reinjected to production depth (Timpany 1990). Prior to 1987, reinjection to production depth was probably less than 1000 tonnes/day.

Fig. 2 shows the changing pattern of withdrawal particularly during the Bore Closure Programme. Parts of the plot before and after the bore closure are largely schematic. I have used Timpany's estimate of summer and winter withdrawal through 1989-90. Fig. 2 has the withdrawal scale inverted for easier comparison with the geothermal monitor well data since increased withdrawal causes decreased pressure. The time of change of withdrawal from summer to winter is not known accurately and I have assumed the change was rapid.

Comparison with the geothermal monitor well records shows the close similarity of the curves for the decrease in withdrawal and the rise in monitor well levels. Below, I relate the gross changes in several monitor well water levels, to the corresponding changes in production. The most prominent features are the seasonal change and the change during the Bore Closure Programme. I divide the Rotorua geothermal field roughly into three sections, according to the gross geological structures.

Gross withdrawal changes

The withdrawal estimates use the closure records and the base-line estimates produced in 1985 (Boreham, 1985). Despite argument about the estimates for some wells, these withdrawal estimates are the only consistent ones tabulated for the whole field at that time. The total withdrawal in Fig. 2 is reduced as each well ceased production by the amount of production of that well. Reliable records of the date wells went out of production and the grouting dates were kept until the official end of the Bore Closure Programme on 31 March 1988. Fig. 2 has been updated to include the estimates of production in July 1988 made by Siitonen (1988) and in 1989-90 by Timpany (1990). Charges for well use introduced with the bore closure have led to voluntary reduction in withdrawal outside the 1.5 km closure zone. New shallow wells, mainly with down-hole heat exchangers, were drilled after the bore closure but official records of them are not available. Overall, there are only minor changes between the 1988 and 1990 estimates.

Total winter withdrawal immediately after the bore closure was about 34% of the value estimated in 1985, and the distribution of withdrawal was quite different. The wells within 1.5 km of Pohutu Geyser had been closed and nearly all the high pressure wells in the east. The number of high pressure wells in the east was small as the chances of drilling a good well were low and some of the existing wells were in poor repair and voluntarily closed; some wells were within 1.5 km of Pohutu Geyser. Also a number of wells in the north have closed, often after agreement between neighbours to use only one well. More re-injection to production depths has occurred.

Many shallow wells were drilled in the closure zone and are either pumped or used with down-hole heat exchangers. Wells less than 70 metres depth are allowed under some circumstances. In some parts of the field, these *shallow* wells are at the same depth as the original production wells. In Rotorua, boiling or near boiling water can lie close to ground surface. The amount of fluid withdrawn from these shallow wells is small; they are mainly removing heat which may or may not effect springs some distance away.

Closure and seasonal change in production

The largest changes in production over a short time span occurred with the bore closure and with the seasonal change. Representative production estimates for wells in different zones (Table 1) shows the winter production as estimated in 1985, the seasonal change as estimated in 1985, the amount of closure defined as the difference in winter withdrawal between 1985 and July 1988, and the ratio $\mathbb{R}_W$ of closure to seasonal difference. The July 1988 production figures are given by Siitonen (1988). Table 2 gives the corresponding monitor well level changes.

Table 1. The 1985 winter production estimates (Winter), the seasonal change (W-S), the amount of closure between 1985 and July 1988 (Closure) and their Ratio R_W (Closure/(W-S)). Production is in tonnes/day. The groupings of the data are geographically based not on strict geological structures. The 1.5 km closure zone and the total for all Rotorua wells are included. The final line includes re-injection to production depth with the closure. Waste from only a small number of wells was re-injected to production depth before the bore closure.

Region	Winter	W-S	Closure	Ratio R_W
Southern ignimbrite	2700	530	2640	5.0
Eastern ignimbrite	3700	880	3430	3.9
Rhyolite	24750	4665	14600	3.1
1.5 km closure zone	10970	1775	10900	6.1
All	31150	6075	20670	3.4
plus reinjection			24000	4.0

Bradford (1988) reported these data in association with the development of a management plan for the Rotorua Geothermal Field by the Bay of Plenty Regional Council. The first three data groupings in Table 1 are based on geographical boundaries rather than strictly on geological structure and have historic relevance only. The southern ignimbrite is roughly south of Sala Street and Arikikapakapa, the eastern ignimbrite is east of Fenton Street, and the rhyolite is the rest of the field. Table 1 includes the numbers for the 1.5 km closure zone and the total production, and also gives the combined deep reinjection and closure for the whole field. The seasonal change is probably the least accurate of the production estimates and errors will propagate to other quantities including it.

For the whole field, the ratio R_W of closure to seasonal change is about 3.4 and increases to about 4.0 if deep reinjection is included. The ratio R_W varies in different parts of the field since both closure and seasonal change were not uniform. For example, the greatest seasonal change occurred in the north where many businesses closed their wells for the summer.

Pressure changes in the production aquifers

Table 2 gives the estimated seasonal change before bore closure in four geothermal monitor well water levels, estimated water-level change caused by closure and the ratio R_L of closure to seasonal change. In most cases, I have given two estimates for the change caused by closure. The lower value is the rise to mid-1988 and the higher value is the rise to the end of 1989. The M12 water level has apparently not risen further during 1989, mainly as a result of a temperature drop in the M12 water column which could have dropped the water level 0.2 m.

Table 2. Estimated seasonal change in some monitor well water levels, estimated water-level change caused by the bore closure and their ratio R_L (Closure/Seasonal). The last two columns indicate the location of the well by region, and whether it was within the 1.5 km closure zone.

Well	Seasonal	Closure	Ratio R_L	Region	1.5 km zone
M12	0.4 m	0.9 m	2.3	Rhyolite	No
M6	0.7 m	1.5-1.9 m	2.1-2.9	Rhyolite	Yes
M16	0.5 m	1.9-2.2 m	3.8-4.4	Ignimbrite (E,S)	Yes
M9	0.5 m	1.6-2.1 m	3.2-4.2	Ignimbrite (E)	No

The values in Table 2 come from data plots with the barometric response removed and they contain large subjective errors. I made allowance for what I thought to be groundwater induced changes in M6 and M12. The withdrawal changes are also estimates so all the numbers compared in the next few paragraphs have unknown errors. The qualitative picture is likely to be correct. Recent changes in M9, possibly caused by boiling in the well, may yield an anomalously high pressure at the end of 1989. Also the shallow groundwater around M9 was disturbed during extensions to the adjacent sewage farm.

Comparing production and pressure changes

Comparing the level ratios $\mathbb{R}_L$ in Table 2 with the withdrawal ratios $\mathbb{R}_W$ in Table 3 shows some consistency. Remember, both $\mathbb{R}_L$ and $\mathbb{R}_W$ are ratios of closure to seasonal change. The values of the water-level change ratio $\mathbb{R}_L$ for M9 agree with the withdrawal change ratio $\mathbb{R}_W$ for the eastern ignimbrite where M9 is located. M16 is located close to the boundary of the eastern and southern ignimbrite and has a slightly higher value of the water-level change ratio $\mathbb{R}_L$ than M9, probably because of an influence of the closure pattern in the southern ignimbrite. Both M9 and M16 have lower values of the water-level change ratios $\mathbb{R}_L$ than the withdrawal change ratio $\mathbb{R}_W$ for the 1.5 km closure zone.

The values of the water-level change ratio $\mathbb{R}_L$ for M6 and M12 are somewhat smaller than the withdrawal change ratio $\mathbb{R}_W$ for the rhyolite or for the whole field. The M6 value of $\mathbb{R}_L$ is a lot smaller than the withdrawal change ratio $\mathbb{R}_W$ for the 1.5 km closure zone which contains M6. The M12 value is also too high to be attributed to local changes (in the north of Rotorua). So I conclude that both M6 and M12 responded to withdrawal changes over the entire region of the rhyolite aquifers and not only to wells immediately around them. Increases in the water level of M6 after the closure may be a result of pressure increases after the closures in the eastern and southern ignimbrite being transmitted to the rhyolite aquifers or from changes induced by rainfall. The widespread similarity of the seasonal change for the rhyolite wells suggests that changes following closure would be similar to those seen in M6 over most of the rhyolite region.

GROSS CHANGES IN GEOTHERMAL PRESSURES

Pressure changes in Rotorua are small compared with those measured in production fields such as Wairakei. The small changes in Rotorua mean that standard modelling and theoretical work on geothermal systems can only give a qualitative picture (my impression is that numerical error in computer models of reasonable size are of the same order as the observed changes at Rotorua). Nevertheless, some useful conclusions can be drawn from quantifying gross changes in withdrawal and geothermal aquifer pressures.

Table 3. Simplified measures of changes in geothermal production and changes in geothermal aquifer pressure measured as a water level.

Total winter geothermal production, 1985	31 000	tonnes/day
Difference winter - summer production, 1985	6 000	tonnes/day
Winter - summer level change in monitor well, M6	0.7	metres
Linear estimate of M6 level rise, total closure	3.6	metres
Historic drop in water levels near M6	5-7	metres
Closure since 1985	20 500	tonnes/day
Closure and reinjection to production depth	24 000	tonnes/day
Rise in M6 level, winter 1986 - winter 1989 measured	1.8	metres

Table 3 contains estimates of changes in Rotorua geothermal production and geothermal aquifer pressure. Aquifer pressure changes measured as changes in water level in well M6 are taken as representative of the Rotorua geothermal field. Simpson (1983) estimated the pressure drop in the production aquifers and found a maximum of 5-7 metres using substantiated well data from the 1960s. The early data is from a small number of wells operating during when the groundwater levels would have been high. The estimates of total production and seasonal change in production (Boreham, 1985) and the seasonal change in geothermal monitor well levels suggest that total closure of all wells could only recover about half the total drop in pressure. The monitor well level rise since the Ministry of Energy Bore Closure Programme suggests an even smaller pressure rise.

Monitor well M6 had one of the largest changes during the bore closure and is located near the area of the largest pressure drop since the 1960s. Changes in other monitor wells on the southern rhyolite were similar to M6 over the times they were measured. I removed barometric and recent rainfall responses as far as possible from the M6 level variation before estimating the gross changes caused by seasonal withdrawal change and by the bore closure. The seasonal change in M6 is before the bore closure.

The predicted increase in aquifer pressure at M6 from bore closure is 2.8 metres assuming no local effects. The increase of 2.8 metres is calculated as the measured seasonal change of 0.7 metres at M6 times the overall $\mathbb{R}_W$ of 4. The figures in Table 3 show a shortfall in recovery of aquifer pressures since the bore closure (1.8 versus 2.8 metres). This shortfall corresponds with the indication from the monitor well data from 1982-1986 that even total closure would not lead to a recovery of 1960s values in geothermal aquifer pressure. The change of 3.6 metres in Table 3 assumes total closure and is calculated as seasonal change at M6 times total production in 1985 divided by the seasonal change in production in 1985.

Rainfall declined between the early 1960s (mean rainfall 1960-64, 1623 mm) and early 1980s (mean rainfall 1980-84, 1257 mm) and this would have caused a decline in deeper groundwater storage. Also, increasing urbanisation around Rotorua may have increased the percentage of rainfall lost in runoff. Rainfall was nearly constant during most of the Rotorua Geothermal Monitoring Programme. So, groundwater storage was declining when geothermal pressure was decreasing through increased withdrawal. Similarly, hot spring failures in the past 20 years (Cody and Lumb, 1992) happened when both geothermal and groundwater pressures were declining. From the values in Table 3, I estimate decline in rainfall caused about half the pressure drop in the Rotorua production aquifers.

One of the reviewers of this paper believes that some of the long-term decline in pressure could also have been due to the long-term effects of withdrawal. This could be so; I have no estimate of the size of such an effect.

CONCLUSIONS

The springs and geysers are the natural expressions of the geothermal aquifer pressure and their flows vary with the geothermal pressure. The main general conclusion from this work is that both geothermal withdrawal and long term-changes in rainfall pattern control the pressures in geothermal aquifers at Rotorua. Man only has control over the amount of geothermal withdrawal allowed, so reducing withdrawal was the only option once the decision to save the springs and geysers at Whakarewarewa was made.

Large errors are involved in estimating the proportionate effects of withdrawal and rainfall on the aquifer pressure, but they appear to be roughly one to one.

Pressure changes transmit easily throughout the shallow geothermal aquifers in Rotorua and the geothermal monitor wells respond quickly to withdrawal changes over a wide area.

Careful cleaning of wrong or uninteresting effects from the data series allows accurate timing of interesting changes and potentially allows relating pressure changes to their cause. This assumes that accurate timing of events which might alter geothermal aquifer pressures is available.

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APPENDIX – LIST OF MONITOR WELLS

A geothermal monitor well network was set up in Rotorua from 1982. Table 3 gives some operational details of the monitor wells used for pressure data. Fig. 1 shows their locations. I have omitted some wells designated as monitor wells for short periods or where the data was poor. Rotorua wells have an RR number and monitor wells may be referred to by their RR number.

Table 4. Locations, drilled depth, approximate recent height of water level, and dates of measurement for those geothermal monitor wells which gave a reasonable amount of pressure data. RR numbers are given for comparison with other data sets.

Name	RR No	Location	Depth (m)	Waterlevel (m asl)	Date from	Date to
M1	305	Government Centre	64.0	289.4	5 Nov 82	23 May 83
					1 Oct 83	17 Jul 85
					15 Jul 87	present
M3	462	Queen Elizabeth II Hospital	140.2	281.5	13 Dec 82	19 Jan 86
					17 Mar 86	22 May 89
M5	684	Carnot Street	175.3	276.5	21 Oct 82	25 Oct 85
M6	777	Goodwin Ave	256.0	280.6	29 Oct 82	present
M7	901	Golf Course	244.4			
M9	889	Sewage Farm	244.5	294.5	28 Jun 84	present
M12	886	Rotorua Public Hospital	75.0	284.4	17 Nov 82	present
M13	868	Forest Research Institute	97.3	291.8	19 Apr 83	2 Oct 86
M14	409	Racecourse	70.1	283.8	15 Nov 83	27 Sep 85
M15	883	Victoria Street	134.0	278.0	2 Dec 83	7 Aug 87
M16	624	Sala Street	156.9	296.2	25 Sep 84	present
M17	724	Waiariki College	156.1	296.3	7 Jul 87	present