# MECHANISMS FOR WATER LEVEL DECLINES IN ALUM LAKES, WAIRAKEI

C.J.BROMLEY[1] & A.W. CLOTWORTHY[2]

[1]Institute of Geological and Nuclear Sciences, Wairakei
[2]Contact Energy Ltd, Wairakei Power Station

**SUMMARY** – Recent water-level declines of several steam-heated pools in the Alum Lakes area of Wairakei have been studied. A mechanism that could explain these declines is gradually reducing steam upflow fiom the underlying depressurising steam zone, causing a change in relative permeability to the counter-flowing liquid and steam. This could eventually allow more liquid through the 2-phase vertical conduit that links the shallow groundwater and the deep vapour zone, and a relatively rapid down-flow then occurs. Other mechanisms involving mudstone drainage and new fractures are also discussed. Equilibrium will be re-established when lateral inflows of groundwater match the new down-flow.

## 1. INTRODUCTION

Declining water levels have recently been observed in some of the themal lakes collectively referred to as the 'Alum Lakes' of the Upper Waiora Valley, Wairakei. (NZ Herald, 17/3/2001, Bromley, 2001). The rate of decline accelerated during early 2001, and some lakes dried up completely. The features most affected are a group of thermal lakes in the 'Mudflat' valley at the south-westem end of the 'Alum Lakes' area, midway between the Western Borefield and the Te Mihi steam field (Figure 1). Water levels, here, receded by about 6 metres between 1997 and August 2001, to about 9 m below their maximum in 1958. Lakes at the south-eastem end of the valley (near bore WK209) also declined, by about 1.5 metres, between January and August 2001. Conversely, the northernmost and largest of the Alum Lakes ("Blue Lake" or "Pirorirori"), has not been affected. Its water level has stayed relatively constant for the past few years.

A hydrothermal eruption occurred on the 22nd or 23rd of March 2001 about 300 metres downstream of the lakes that had declined most in level. There were no reports from anyone who witnessed or heard the eruption, but it flattened about 1 hectare of pine trees and formed a crater about 20 x 30 m in size (NZ Herald, 29/3/2001).

Long term groundwater level declines have previously occurred elsewhere at Wairakei and Tauhara, specifically in an area between the eastern and western borefields (up to 30m) and within the northern part of the adjoining Tauhara geothermal field (1 to 2 m/decade). Various mechanisms for these long term groundwater level declines have previously been suggested, including a delayed response to deep reservoir pressure decline, mudstone drainage (Allis, 2000), reduced recharge, and increased leakage through newly created fractures (Bromley et al, 1996).

In this paper, we present the evidence for recent changes in the local groundwater surface affecting some of the Alum Lakes, and we discuss likely mechanisms that can account for both long term and short term water level declines.

## 2. ALUM LAKES HISTORICAL CHANGES

A detailed, pre-development description of the hot springs, pools and lakes of the Upper Waiora Valley ('Alum Lakes') was given by Gregg and Laing (1951). The historical flow-rate, temperature and chemical data are summarised in Bromley (2001). In 1951, all the hot pools and springs were steam heated and acidic (pH <3) with increasing chloride concentrations and sinter deposits around springs at lower elevations.

The northern source of the Kiriohineki Stream 'Pirorirori' (Alum Lake, DSIR#403) probably occupies a pre-historic hydrothermal eruption crater. Occasional discharges into this lake of high chloride geothermal water from Te Mihi wells have influenced its chemistry (9 mg/kg Cl in 1951; 106 mg/kg in 1997). Inflowing groundwater springs have always maintained the lake to within a few centimetres of the outlet level, but there has been no significant overflow for several years. Temperatures have reduced over 50 years fiom 47°C to 33°C and the pH has increased, implying less steam heating. The lake's colour has changed fiom 'blue-grey cloudy' to a deep green (probably fiom algae).

Butterfly Spring (#418), a southwestern tributary of Kiriohineki Stream, originally discharged 7.5 l/s in 1951. By 1997, discharge had ceased. Pool water levels have since steadily receded.

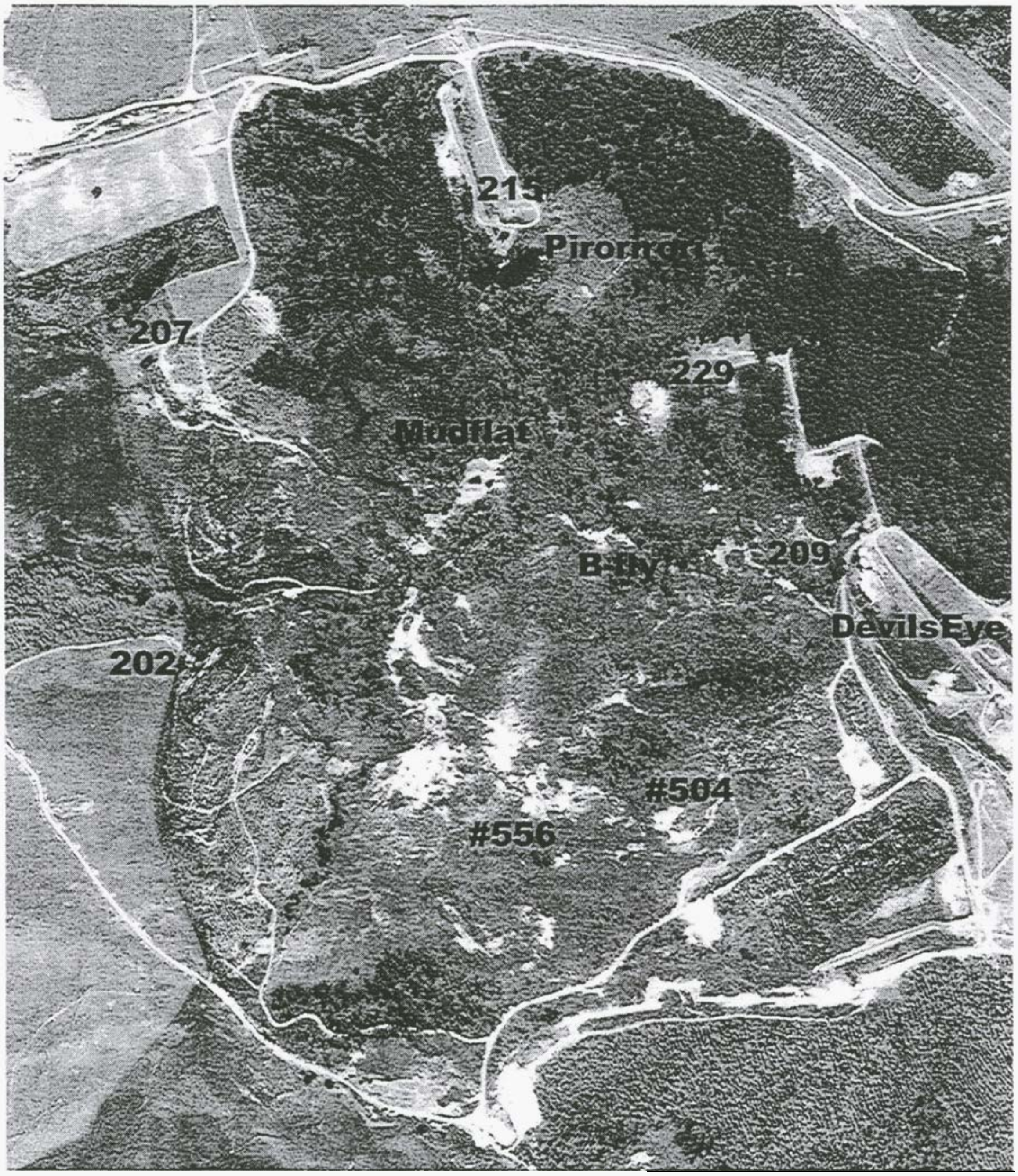


**Figure 1.** Aerial photograph of Alum Lakes area- 16/10/1999 (from Contact Energy).

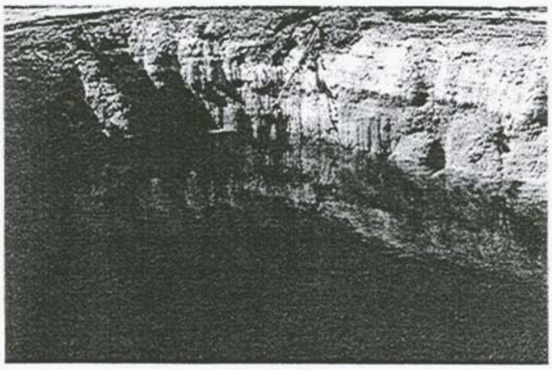

**Figure 1a.** W-east, mudflat pool, 24/10/97

**Figure 1b.** W-east, mudflat pool 17/11/00

However, pH and chloride concentration have remained stable (2.3, 120 mg/kg) for 50 years.

The 'Mudflat' thermal pools west of Butterfly Spring are located in an elongated depression, which is floored with solid mud, and almost devoid of vegetation (Gregg and Laing, 1951). In 1958, the area became flooded and was described as a 'Crater Lake' by Fisher (1959), with a surface area of 6900 $m^2$ and temperature of 40°C. The flooding was caused by rising groundwater levels, in response to several years of increased rainfall. Water levels later dropped about 2 m, but fluctuated with long term rainfall trends, and with intermittent discharges of separated geothermal water from bore WK207.

WK209 Lake (#502) is located along the Kiriohineki Stream at the southeastern end of the valley. The natural heat discharged through the lake was relatively constant between 1950 and 1980. However, by July 1997, flowrates had dropped to about 13 l/s at 45°C at the nearby road culvert. Monitoring since August 1999 at a weir above the culvert has shown a steady decline in stream flow from about 16 l/s to zero discharge in January 2001 (Fig. 2). Water levels in the WK209 Lake then started to decline.

Devil's Eyeglass Springs (#491 and #492) are located on the steam bank about 100 m below the culvert weir. They have remained constant in flow rate, temperature and pH since the initial 1951 survey, and unaffected by the water level declines in the neighbouring Alum Lakes area. The chloride concentration has declined, however, from around 670 mg/kg in 1951 (50% deep chloride water), to about 150 mg/kg in 1997.

## 3. RECENT LAKE LEVEL CHANGES

An infrared survey conducted in July 1997 mapped the active thermal areas at Alum lakes in detail. Since then, photographs and measurements of spring flow rates and temperatures in the Alum Lakes area have been taken on five separate occasions. Photographic sequences from these sets show the changes that have occurred over the' past four years (Fig.1a,1b, and Bromley, 2001). Since Nov. 2000 repeat level measurements of water surfaces have been made using a real-time differential Leica GPS instrument. Where necessary, a pole-base (pool rim) to water-level correction was applied using a float suspended from a horizontal pole. The results of these measurements are recorded in Table 1, and illustrated in Figure 2.

The water levels of the lakes in the 'Mudflat' area, (w-a to w-n) and Butterfly Pool (B-fly), declined between 1997 and 2000 at an average rate of about 1 m/year (based on level estimates from photos). Between Nov. 2000 and April 2001, the decline rate increased to about 5.4 dyr. This increased rate is greater than the long-term water-level decline rate in some Eastern Borefield groundwater bores, which reached a maximum in the 1980s of about 3 m/yr (e.g. bore 14/0). However, between April and August 2001, the Mudflat decline rates reduced to about 4 m/yr, suggesting that some lateral recharge is having an effect, and that the present water level declines may eventually level out. Temperatures of most 'Mudflat' lakes have also declined from 52-57°C (July 1997) to 36-42°C (Nov. 2000). This suggests a reduction in steam heating.

The water level in Pirorirori ('Alum Lake') has not changed significantly since 1951. The WK209 Lake also did not change until about Jan. 2001, when the Kiriohineki Stream ceased flowing. The lake and neighbouring pools have since dropped in level by about 1.5 m.

Repeat measurements of pool #504 (Fig. 1) have shown that it has changed from a discharging acid spring (67°C, 0.32 l/s) in July 1997, to a boiling pool, 1.1 m lower in level, by April 2001. The elevation of this steam-heated pool (467 m) is about 35 m above the level of the regional groundwater aquifer (based on data from surrounding bores). It is probably connected to a small locally 'perched' aquifer, which is poorly connected to the regional groundwater. Such pools can exist at high elevation because a sealing layer of hydrothermal clay alteration hydrologically isolates them. Steam condensate and rainfall recharge the pool. The water level decline since 1997 is an indication that the local recharge has diminished, that is, less steam is rising to the surface.

## 4. HYDROTHERMAL ERUPTIONS

The location of a hydrothermal eruption, that occurred on or about 22/3/2001, is given in Table 1 and located on Figure 3 (labelled 'hyd') midway between Butterfly Pool and WK209 Lake. It erupted from a small (3-m diameter), near-boiling pool in the original bed of the Kiriohineki Stream, to form a large crater. On 11/4/2001 the crater was weakly steaming, had a pH of 3.0, and the water level was 1-m above the nearby W-209 Lake. Since April, water levels in this crater have declined at a rate of about 0.2 m/month. The most likely triggering mechanism for this eruption was the effect of the locally declining water levels on the near-boiling pool. If pressures reduce sufficiently rapidly, boiling is initiated, and surface material may be ejected from the vent area. This reduces pressures further, deeper boiling is initiated, and the resulting chain reaction can develop into an eruption.

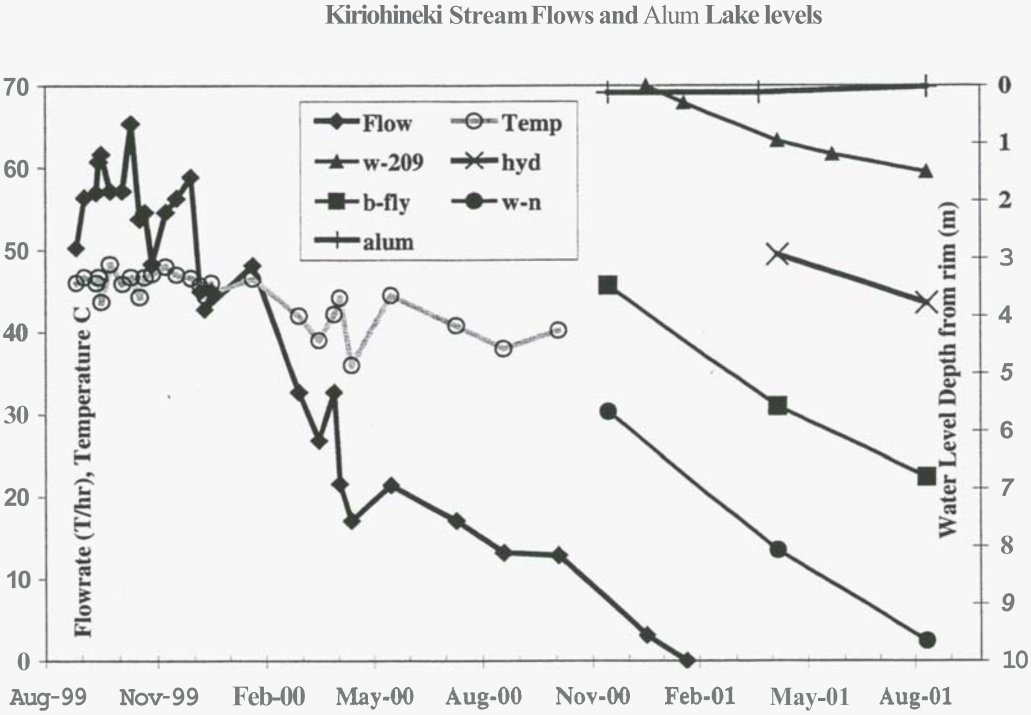


Figure 2. Kiriohineki Stream flow and temperature, at culvert weir near Wk209, from 1999, then water level depths (from the pool rim) of five nearby lakes and pools (Figs. 1 and 3), from Nov. 2000.

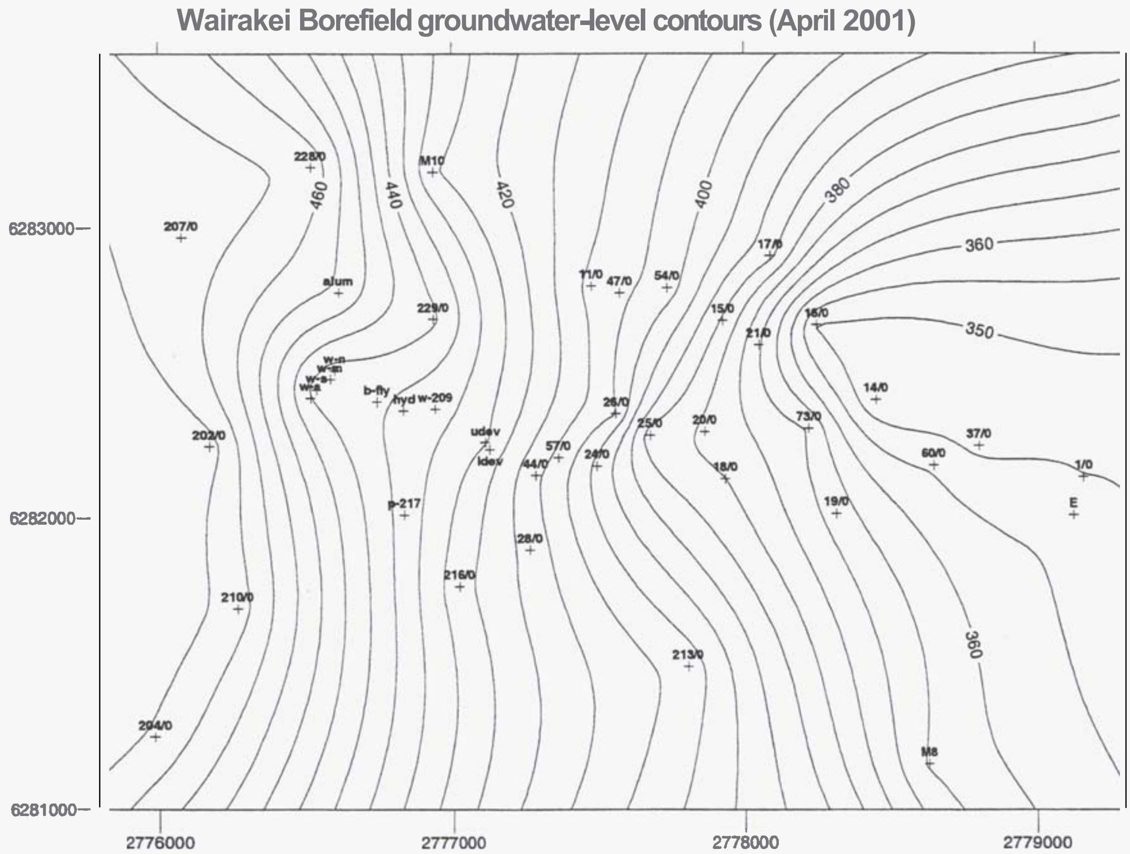


Figure 3. Wairakei Borefield April 2001 groundwater level contours (5m intervals) showing west to east gradients and two areas of anomalous water level decline: the Eastern Borefield (14/0) and the Mudflat area of Alum Lakes ("B-fly"). Crosses mark positions of groundwater bores, lakes, or springs.

Smaller mud eruptions have also been reported from other vents in this area. For example, a nearby mudpot (located 65 m NE of Butterfly Pool) was reported by a helicopter pilot in 1997 to have spouted mud to about treetop height. More recently, a 'perched' acid pool (#556) near the top of Waiora Hill was observed to have erupted mud across neighbouring vegetation between 29/3/2001 and 3/4/2001. Such eruptions often occur after a relatively dry summer when local water levels have declined because of reduced rainfall recharge (Bromley et al, 1994).

## 5. GROUNDWATER LEVEL CHANGES

Groundwater level changes at Wairakei have been recorded in many monitor bores since about 1955. Between 1956 and 1995, a 'cone' of groundwater level depression, centred near bores 14/0 and 16/0 (Fig.3), developed at the junction of the Eastern and Western Borefields. Within about 1-km radius, water levels had declined by more than 10 m, with a central maximum decline of about 30m. During the 1990s, water levels in the Borefield 'cone of depression' area stabilised at a reduced level just above that of the pond (347.4 m), in the Wairakei Stream (below Geyser Valley). This suggests hydrological control by the pond on the groundwater levels in the Eastern Borefield.

Contours of the groundwater level surface for the Wairakei Borefield area, as of April 2001, are presented in Figure 3. As well as recent data from the groundwater bores, this contour map uses level data from water surfaces in the Alum Lakes area and Devils Eyeglass Springs. The resulting map shows a west-to-east gradient in the water-level surface, implying regional groundwater flow towards the lower Wairakei Stream and Waikato River. The contours are not significantly affected by local terrain, but there are two notable 'embayments' in the contours where water levels have dropped: the Eastern Borefield 'cone of depression', and the Mudflat Lakes area. The smooth contour gradients through the Alum Lakes area are consistent with the hypothesis that the water levels in these lakes and pools represent the local groundwater surface.

Groundwater level data from most bores south and west of the Alum Lakes area (eg 207/0, 202/0) show a normal rainfall response (1-3m), with a time lag of up to 1 year. Fig. 4 illustrates the correlation between annual rainfall (running 12 month total) and water levels in Te Mihi g/w bores. Bores 228/0 and 229/0 have shown a gradual water level decline of about 1m since the mid 1990's, relative to #68.26 (5 km to the NW, outside the field). The nearest bores to Alum Lakes in the Western Borefield show a long-term water-level decline since 1960, varying between 7 m and 23 m, with a steepening decline rate commencing about 1982 to 1986.

The steepening of groundwater decline rate during the mid 1980s was also observed in several of the Eastern Borefield bores (14/0, 37/0, 60/0). Allis (2000) sought to fit these water level decline curves using a layered subsidence model for the Eastern Borefield. His model obtained an approximate fit by using a low permeability, but highly compressible, mudstone layer separating the groundwater from the underlying steam zone. The model predicted a steepening of the groundwater level decline rate by about 1980. The low permeability mudstone is an 'aquitard', not a perfect cap; it attenuates and delays (by several decades) the effect of deep pressure drawdown on shallow groundwater levels. The model demonstrates that the permeability and thickness of the mudstone aquitard (which varies across the Wairakei field) principally determine the timing of the onset of groundwater level decline, and the subsequent rate of decline. The rate of groundwater decline is always less than the underlying steam pressure decline. If the water level decline rate is sufficiently slow, and horizontal permeability in the groundwater aquifer is sufficiently high, then lateral recharge from surrounding groundwater, or from surface water (such as the ponded Wairakei Stream), can also occur. This allows groundwater levels to stabilise, as has been observed in the Eastern Borefield.

## 6. MECHANISMS FOR WATER LEVEL DECLINE

There are several plausible mechanisms or causes contributing to the declining pool water levels in part of the Alum Lakes area. The most likely mechanisms (which are not all independent), are: underlying steam pressure drawdown, reduced upflows of steam, mudstone aquitard drainage, and new fractures. These are discussed in more detail below, after an initial consideration of the effects of rainfall changes.

Long-term rainfall changes have clearly affected both pool water levels and surrounding groundwater levels (up to 3m) in the past, and declining rainfall between 1996 and 2000 (Fig. 4) may have contributed to the observed water level declines since 1997. However, rainfall deficit does not account for the 6-m drop now observed in several pool water levels, nor the increased decline rate after December 2000, while rainfall has been increasing. Therefore, changes in rainfall recharge are discounted as the principal mechanism for the recent water level declines.

Plausible Mechanisms:

a) Steam pressure drawdown: Southwest steam zone pressure (at about 300m depth) has declined by about 15 bars since 1960 at an almost linear

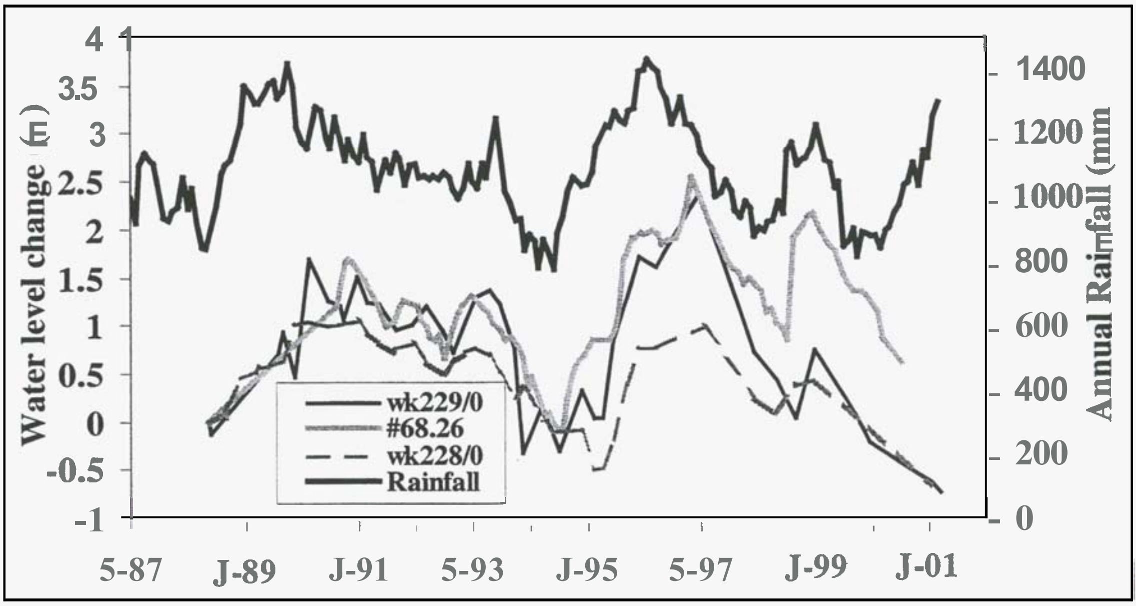


**Figure 4.** Wairakei groundwater level changes, since 1987, in selected bores near Alum Lakes (see Fig. 1.), showing correlation with changes in annual rainfall (running 12-month total). Bore #68.26, located outside the Wairakei Field, is included for comparison.

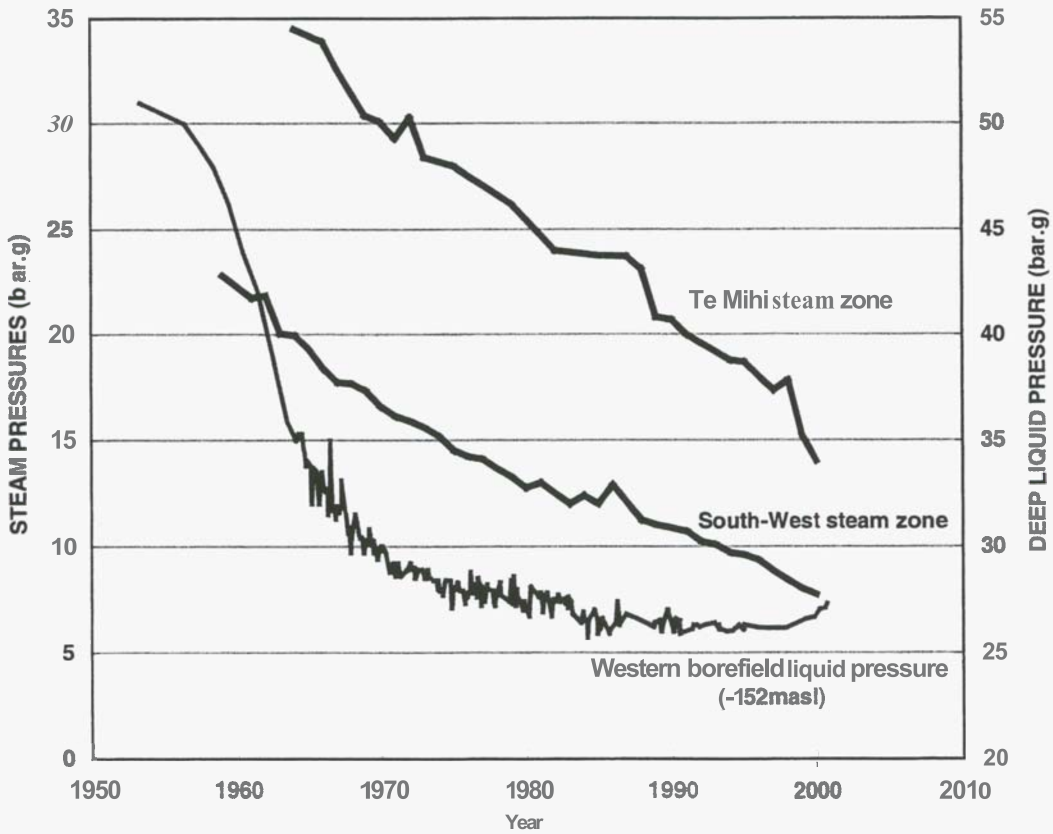


**Figure 5.** Wairakei pressure changes in the deep liquid and shallow steam zones (from Contact Energy records, Clotworthy, 1998)

rate of **0.37** bars/year (Clotworthy **1998,** Fig. **5).** If directly transmitted to the groundwater, this would be equivalent to a steady water level change of about **3.7** m/year, which has not been observed. Although the steam pressure drawdown since **1960** is apparently not ***directly*** linked to the water level declines there is an ***indirect*** link through the mechanism described below.

b) ***Reduced upflows of steam:*** Natural chokes form in a reservoir between a vapour zone (initially at **33 bars** pressure) and an overlying liquid zone, and these restrict the counter-flow of water and steam within the fractured conduits (or "heat pipes") that link them (Jenson, **1984).** In the Alum Lakes catchment, during the **1950's** and 60's, the total mass flow of steam that was rising and condensing into the groundwater was a significant proportion (estimated at 50%) of the total groundwater discharge (based on stream temperatures). South-West steam pressure has reduced since **1960** (Fig. 5) and is now **–8** bars-g, much closer to the pressure **(–7** bars) at the base of the groundwater aquifer **(370mRL,** top of the mudstone). Therefore the upflow of steam into the groundwater will have reduced. This is likely to have caused the observed cooling of many of the Alum Lakes. Reduced liquid recharge (condensed steam) will contribute to a gradual drop in water level. Furthermore, as the steam pressure drops, and the upflow of steam through fractures to the surface diminishes, the water saturation in these fiactures will increase. Once saturation exceeds about **50%** there is a more rapid increase in the relative permeability of the counter-flowing water in the fractures, compared to that of steam. Water down-flow then rapidly increases. If the down-flow of water exceeds the rate at which it can be locally replenished from surrounding groundwater, then the lakes drain rapidly.

A similar phenomenon was observed at WK204, the 'Rogue Bore'. In **1960,** after a casing failure at **120m** depth, a steam eruption created a **30m** deep crater, which filled with groundwater. For 13 years this small lake geysered and overflowed as the underlying steam pressure gradually dropped. Then, in Oct. **1973,** over a period of just **1** month, the water level dropped **20m** and temperature dropped from **74°** to **26°** (Thompson **1977).** It has since remained empty, dry and cold. A similar effect may explain the acceleration in groundwater level decline in the Eastern Borefield in the **1980s,** when underlying steam pressures dropped below **8** bars(g).

c) ***Mudstone aquitard drainage:*** Gradual mudstone drainage provides another plausible explanation for the delayed groundwater level decline in the Eastern Borefield area, that accelerated during the early **1980s.** Variations in the thickness and permeability of the mudstone aquitard separating the groundwater from the underlying geothermal aquifers occur across the field. In the Alum Lakes area, the permeability and thickness may be such that the effects on groundwater from pressure drawdown in the Te Mihi steam zone, which commenced in **1965,** were not apparent until the mid **1990's.** However, modelling by Allis (2000) of the upward diffusion of pressure draw-down through the mudstone suggests that the change in rate of decline would happen smoothly over many years, not abruptly. The final water level decline rate would be no more than **–1** m/year. Therefore, another mechanism is needed to account for the more rapid changes that were recently observed (up to **5.4** m/year).

d) ***New fractures:*** **During** our visit to photographically record thermal features in Nov. **1999,** new steaming cracks, several metres long, were noted. Located midway between the 'Mudflat' lakes and 'Butterfly' pool they are oriented north-east. Such features provide evidence for new fractures in this area. These may have formed during one of the swarms of shallow (–5 **km** depth), low-magnitude **(M<4)** tectonic earthquakes that occur along the NE-trending Taupo Fault Belt. Between **1987** and **1998, 20** shallow earthquakes (2.4<M<3.8) were located within 5 km radius of the Alum Lakes area. Since **1999,** there has been an average of **12** of these local earthquakes recorded per year. **(S.** Sherburn, pers.comm.)

Such new fractures, of limited length, would not only allow some steam to rise to the surface from the heated groundwater aquifer but would also locally facilitate increased downflows of this groundwater, through the mudstone aquitard and into the underlying steam zone. This is therefore a viable mechanism for a more rapid local decline in groundwater level.

## 7. CONCLUSIONS

Water levels in a group of thermal lakes in the 'Mudflat' area of **Alum** Lakes, and at nearby 'Butterfly Pool', have declined by about 6 m since **1997.** The decline rate increased after Nov. 2000 but is now reducing. A nearby hydrothermal eruption in March **2001** was probably triggered by the rapidly declining water levels. Further down the valley, flows in the stream declined from Nov. **1999.** The W-209 Lake stopped discharging water to the Kiriohineki Stream by Jan. **2001** and then declined in water level. The 'Mudflat' lakes also declined in temperature by about 15°C over three years. The northern **'Pirorirori'** lake and the southern springs ('Devils Eyeglass') were unaffected. All the springs and pools are acidic, with minor chloride concentrations of about **100** mg/kg. They are dominantly fed by condensed steam and gas mixed with groundwater.

Several plausible mechanisms for the recent water level declines are proposed: steam pressure drawdown, reduced steam upflows, mudstone aquitard drainage, and drainage through new fractures created by earthquakes. Of these, the most likely mechanism is reduced steam upflows. The area of previous groundwater level declines that was centred between the eastern and western borefields has now expanded further to the west, into the Alum Lakes area.

Over the next few years, higher than average rainfall could raise regional groundwater levels by two to three metres, and help to counteract the present water level decline in the pools. However, in the long term, it is predicted that full restoration of the affected lake levels and stream discharge, is unlikely to occur naturally. The water levels will probably continue to decline (with some rainfall variation) until a new equilibrium is established, with recharge occurring fiom lateral inflows of surrounding groundwater.

## 8. ACKNOWLEGEMENTS

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**Table 1.** Recent water levels and temperatures - Alum Lakes area.

| Name (Fin 1) | DSIR # | East (m) | North (m) | Date | Water L. (mRL) | Water L.- from rim | Temp. °C |
|---|---|---|---|---|---|---|---|
| alum | 403 | 2776608 | 6282776 | 17/11/00 | 454.14 | 0.12 | 31.4 |
| | | | | 26/03/01 | 454.14 | 0.12 | 33 |
| | | | | 17/08/01 | 454.20 | 0.02 | |
| w-a | 433 | 2776510 | 6282412 | 17/11/00 | 440.48 | 3.7 | |
| w-s | 433 | 2776532 | 6282440 | 11/04/01 | 437.59 | 7.3 | |
| w-m | 506 | 2776578 | 6282478 | 11/04/01 | 437.64 | 7.57 | 42.5 |
| w-n | 508 | 2776594 | 6282507 | 17/11/00 | 440.53 | 5.67 | 36 |
| | | | | 11/04/01 | 438.13 | 8.07 | 37 |
| | | | | 17/08/01 | 436.55 | 9.65 | |
| B-fly | 418 | 2776737 | 6282399 | 17/11/00 | 438.6 | 3.48 | 97 |
| | | | | 11/04/01 | 436.62 | 5.58 | 97.1 |
| | | | | 17/08/01 | 435.40 | 6.8 | |
| hyd | | 2776829 | 6282369 | 11/04/01 | 432.75 | 2.94 | |
| | | | | 17/08/01 | 431.91 | 3.78 | |
| w-209 | 502 | 2776940 | 6282374 | 20/12/00 | 432.72 | 0 | |
| | | | | 22/01/01 | 432.42 | 0.3 | |
| | | | | 11/04/01 | 431.76 | 0.96 | |
| | | | | 28/05/01 | 431.52 | 1.2 | |
| | | | | 17/08/01 | 431.22 | 1.5 | 93 |
| p-217 | 504 | 2776831 | 6282011 | 11/04/01 | 466.95 | 1.2 | 95.3 |