CHANGES IN SHALLOW HYDROLOGY OF THE TAUHARA GEOTHERMAL FIELD

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SUMMARY - The shallow hydrology at Tauhara has been affected, in the north, by rainfall recharge (with about a 6-month response lag), a steady 1 to 2 m per decade drawdown, and temperature changes from a steam heating thermal pulse caused by deep pressure drawdown. Southern Tauhara springs and bores have responded only to rainfall trends and lake level variations, respectively. Although the major impacts from Wairakei drawdown have already occurred, future Tauhara developments could result in further shallow hydrological and thermal effects, particularly if pressures in the underlying steam zone are modified by steam extraction or water injection.

1. INTRODUCTION

Over the past decade a large quantity of hydrological data have been collected from the Tauhara Geothermal Field, near Taupo, New Zealand, to monitor the behaviour of the shallow thermal aquifers. Most of these data, which include flow rates and temperatures of major discharging springs, water levels and temperatures of selected shallow boreholes, and fluid and gas chemistry of samples from bores and springs, were collected by, or on behalf of, Environment Waikato (Regional Council).

Previous reviews of the shallow hydrology at Tauhara were undertaken by DSIR staff in the 1980s (Allis, 1983; Dawson, 1988; Dawson and Thompson, 1981). DSIR staff also compiled an assessment of the development impacts and reservoir response of the Tauhara Field for the Waikato Valley Authority in 1988, and this included a chapter on shallow hydrological impacts and changes noted fiom hot spring and bore measurements. Recent reports to Environment Waikato (Bromley, 1995, Glover and Klyen, 1996) updated these earlier assessments, reviewed the recent data and discussed probable causes of the observed changes.

Impacts on the environment caused by geothermal development, and in particular changes to natural thermal features and thermal groundwater aquifers, are an issue of significance under the Resource Management Act consent process for intending geothermal developers in New Zealand. Research into the causes and effects of such changes at Tauhara which followed development of the adjoining Wairakei Geothermal Field, has also attracted international attention because of the long history of welldocumented measurements, and the implications for long-term behaviour of similar geothermal systems overseas. Local interest in the behaviour of the shallow aquifers has also been aroused in recent times because of several applications to develop Tauhara Geothermal Field for electricity generation. A large number of domestic bores, together with two significant hot spring resorts (AC Baths and De Bretts) currently make use of the shallow heat and natural thermal waters, and their owners have a strong interest in preserving or enhancing the Tauhara shallow thermal resource. Predictions of any future impacts on this resource caused by deep fluid extraction and reinjection for additional power development will attract considerable interest and debate. This paper attempts to provide an objective overview of the monitoring that has taken place, and to set the scene for such a debate with initial suggestions as to possible future impacts.

2. SHALLOW HYDROLOGY

The stratigraphic sequence in the Tauhara and Wairakei areas (Wood, 1994) commences with Taupo Pumice Alluvium (1800 a) and Taupo Super Group (10 ka ignimbrite and pumice deposits) which host shallow aquifers. This is underlain by POS (Post-Oruanui Sediments) containing siltstones and mudstones. These sediments act as aquicludes separating the shallow perched aquifers from deeper aquifers in the underlying Oruanui Formation (23 ka pyroclastic flow tuffs), and portions of the Huka Falls Formation. The Huka Falls Formation contains a sequence of inter-layered sedimentary formations, including mudstone aquicludes (Hu1, Hu3) and breccias, tuffs or sandstones forming aquifers (Hu2, Hu4). The underlying Waiora Formation consists of a similar set of alternating aquifers and aquicludes. The Tauhara dacite dome (190 ka) to the east disrupts the sediments, and provides a recharge source of groundwater, diluting or quenching the upflowing geothermal fluids in Tauhara aquifers.

Dawson (1988) interpreted the shallow hydrology using resistivity, downhole temperatures and drillhole stratigraphy. Upper and lower groundwater aquifers were identified and their temperatures and water levels contoured, using 1979 data. Pressure measurements from inferred feed zone depths in Tauhara wells, when plotted against depth (Allis, 1983), reveal the perched nature of the shallow aquifers. Most measurements fall on one of three linear hydraulic gradients, implying three primary aquifers. The uppermost aquifer has a piezometric Surface at about 400 masl. This coincides with the elevation of Kathleen and AC Springs to the north (Fig. 1), although the Waipahihi Springs to the south are 20 m higher and probably isolated fiom the northern features. The underlying aquifer (also perched) has an apparent water level at about 360 masl (similar to lake level) and occurs within the Oruanui tuff, Hu4 and Hu2 formations. These shallow aquifers overlap within a broad zone (1 to 2 km wide) extending from the Spa Sights area near the Waikato River, to Waipahihi Springs in the south. A third, deep aquifer occurs below sea level, mostly within the Waiora Formation. Within this deep aquifer, pressure drawdown fiom Wairakei production has created a steam zone which has induced changes in the nature of the overlying shallow thermal aquifers in the northern and central Tauhara area. The presence of this steam zone has allowed an increased upward flux of steam into overlying aquifers, but a decrease in upflow of hot chloride water (as at Wairakei). Consequently, chloride springs and geysers at Spa Sights (Waikato River) dried up in the 1960s and 1970s, while temperatures of the steam-heated groundwaters steadily increased.

The chemistry of Tauhara discharges was discussed by Glover *et al.* (1989) and Henley and Stewart (1983). Consideration of the deep chloride fluids, using mixing models, suggests that there are two separate hot fluid sources at Tauhara: one of about 1600 ppm chloride which underlies the northern part of the field and was affected by Wairakei pressure drawdown; and the other of about 700 ppm chloride (and different oxygen/deuterium isotope signature) which feeds the southern (Waipahihi) sector, and is postulated to originate fiom a separate reservoir beneath Mt Tauhara (Allis *et al.* 1989). A separate source provides pressure support and explains the lack of hot spring interference effects observed in the Waipahihi springs and neighbouring bores to the south.

To the north of Tauhara Road the lake level aquifer has a chloride content that has decreased significantly with time, caused by reduced hot fluid recharge, increased steam heating and dilution by groundwater. The upper aquifer chemistry now varies fiom diluted chloride/bicarbonate waters near Waipahihi (south Taupo), through steam-heated sulphate waters in the central area, to mixed sulphate-bicarbonate steam-heated waters in the north. Higher bicarbonate values tend to occur at the cooler margins of the aquifers. Steam condensate isotope data (^{18}O and D) also reveal a difference between primary steam originating fiom the deep boiling aquifer (such as at the Spa Hotel borehole and Pony Club fumarole) and secondary steam boiled fiom the shallow steam-heated aquifer (such as near the Industrial Zone and Tauhara College). Isotope data also shows that Lake Taupo water is isotopically distinct and therefore not a major component of meteoric recharge to the Tauhara Field (despite good pressure connection near the lake edge).

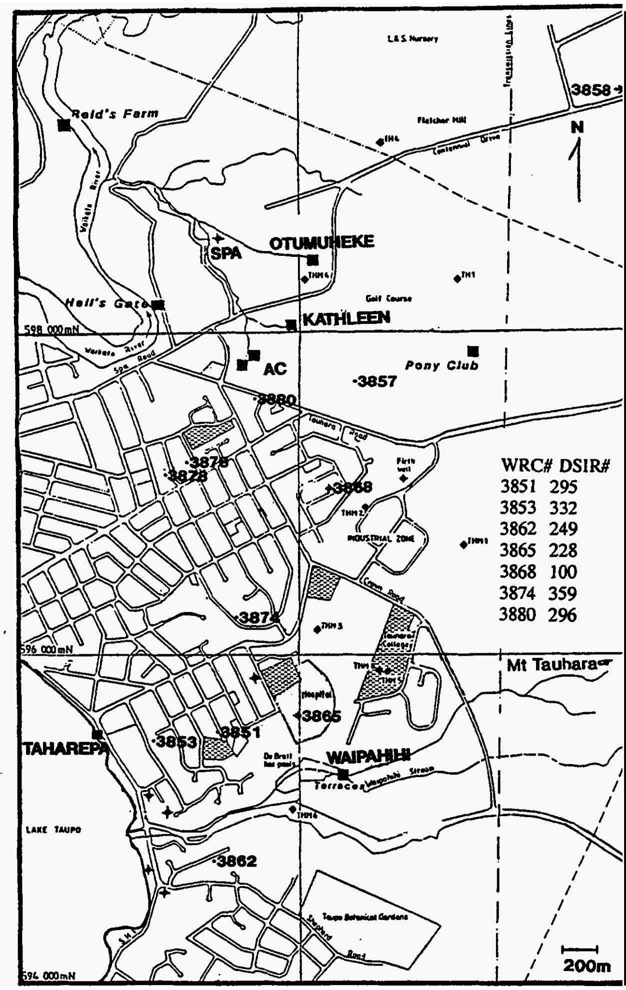


Fig. 1 - Location map of Tauhara thermal features and boreholes referred to in this paper.

3. RECENT HYDROLOGICAL AND GEOCHEMICAL CHANGES

3.1 Springs

The results of regular monitoring, since 1987, of the flowrates of four major Taupo springs (Kathleen, AC, Otumuheke and Waipahihi, see Fig. 1) show the effects of long-term rainfall recharge to the perched aquifers. Figure 2 shows a comparison between the flowrates and rainfall. Rainfall peaks in 1989 and 1995/96 coincide with discharge maxima. The demise of the Kathleen Spring in February 1993 can be partly attributed to a period of several years of declining rainfall; its resurrection in October 1995 occurred after a year of

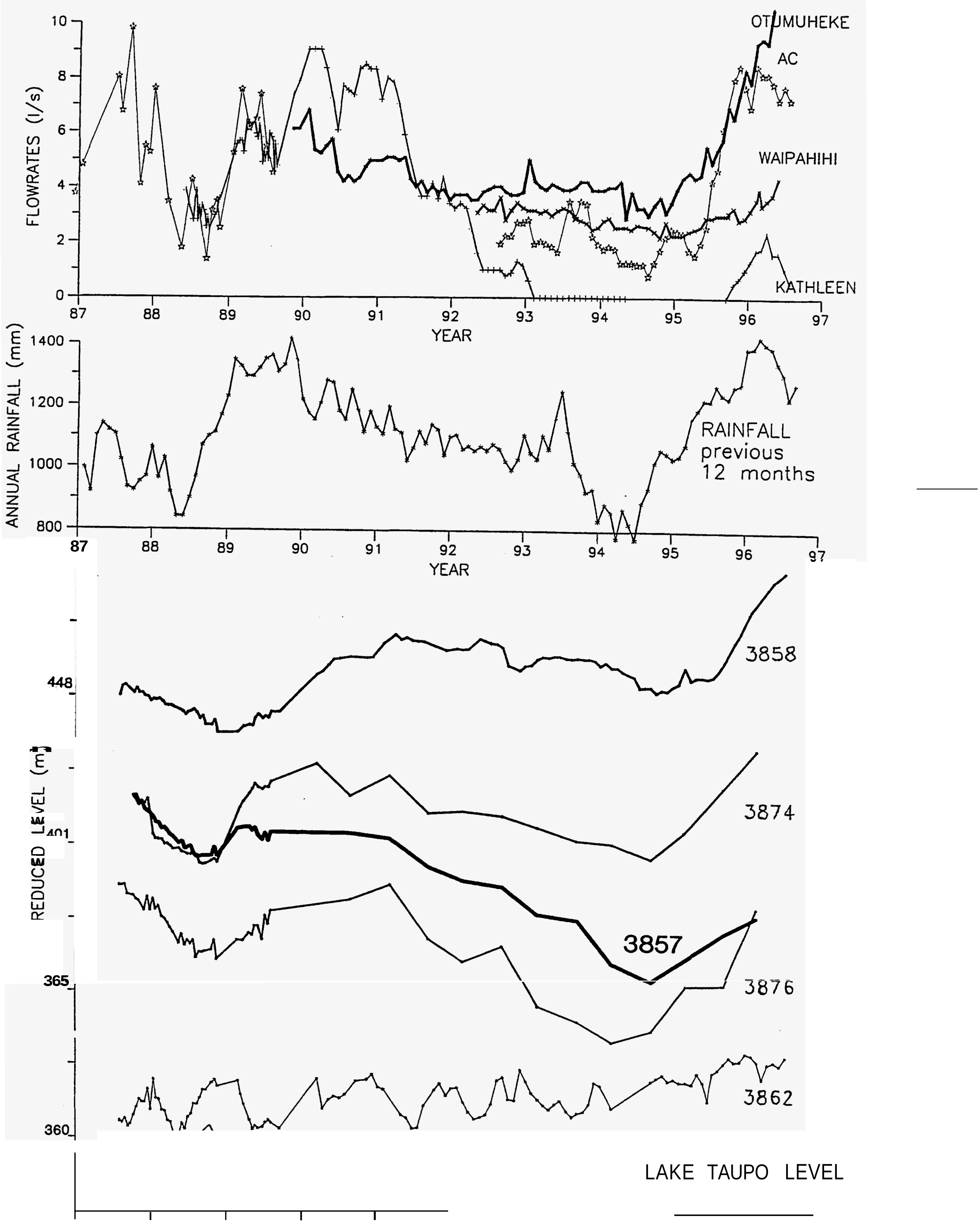
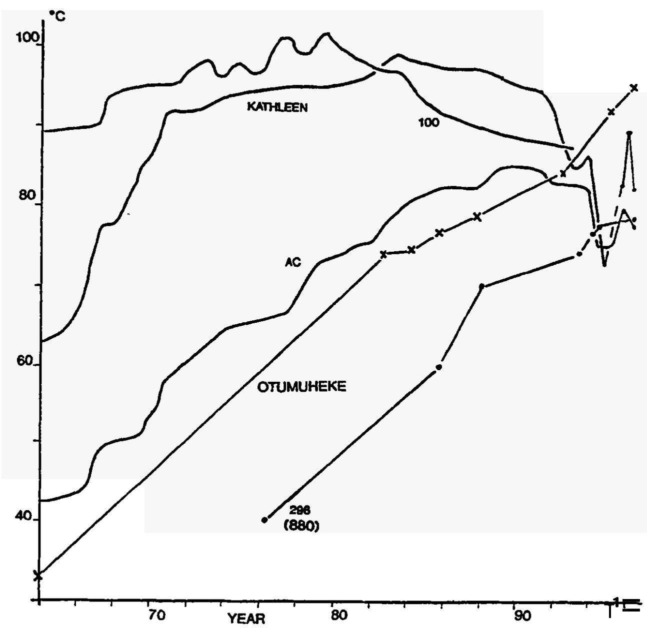


Fig. 2 - Comparison of Tauhara hot spring flow rates, annual **rainfall, shallow borehole water levels and lake level variations. Boreholes labelled according to Environment Waikato** Wellarc number.

relatively high rainfall. Superimposed on the long-term rainfall response there is an annual cycle in the flowrates of the northern springs (near AC Baths), with a minima in winter. It was initially thought that draw-off from pumped domestic wells in winter causes this cycling, but most nearby wells operate all year round, and the closest pumped shallow bore on the Taupo Golf Course operates predominantly during summer to provide water for irrigation (after cooling). The timing of the flowrate maxima in summer could alternatively be the result of several months delay between infiltrating winter rainfall recharge and subsequent thermal groundwater level response. Comparison of monthly rainfall with spring flow rates supports this interpretation.



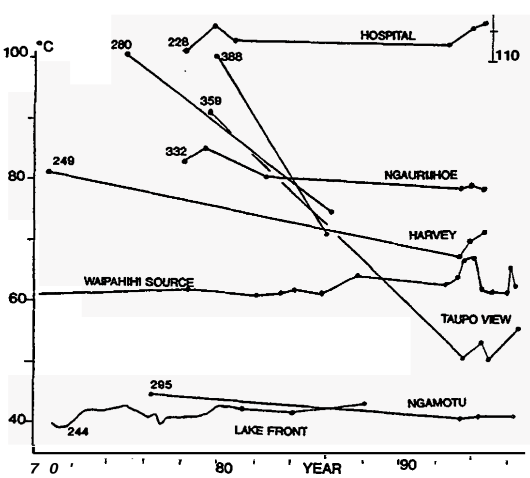


Fig. 3 - Temperature changes of Tauhara springs and shallow bores (labelled with **DSIR** catalogue numbers) showing effects of the thermal pulse.

Temperature measurements of spring discharges, however, show different trends (see Fig. 3). A continuing linear increase of about 2°C per year at Otumuheke (from 33°C in 1964 to 95°C in 1996) is caused by the steam-heating thermal pulse, which also affected the Kathleen and AC spring temperatures in the 1960s and 70s. However, at the latter two springs, which had higher predevelopment temperatures of about 62°C and 42°C, the temperatures levelled off in the 1980s as they approached boiling point and extra heat was released through steam. Because these springs are at a higher elevation they are also more susceptible to groundwater level decline. Consequently, as flow rates dropped in the 1990s, the temperatures also dropped (in 1991 at Kathleen Spring and 1994 at AC Spring), because of greater atmospheric cooling near the water table and the spring vent.

In future, the temperature of Otumuheke Spring will probably follow the pattern of Kathleen Spring, levelling off at near boiling temperatures and changing in response to any major flowrate variations. Further reductions in deep steam zone pressures would probably result in gradual reductions in secondary steam heating of overlying aquifers, and eventual temperature declines of these northern springs.

By comparison, the temperatures and flowrates of the Waipahihi source spring (south Taupo) have stayed relatively constant. Flowrates have varied in response to long term rainfall changes, but temperatures have remained at about 65°C ± 4°C since the 1960s.

3.2 Boreholes

Regular monitoring (since about 1987) of water levels in selected Taupo boreholes (Fig. 2) further confirms the influence of long term rainfall changes on the upper aquifer, and also illustrates the influence of seasonal lake level changes on water levels in the lower aquifer, detectable to within about 1 km of the lake shore. One of the most significant findings is that there appears to be a long term decline in upper aquifer water levels of about 1 m to 2 m per decade over the northern part of the thermal aquifer. Cold groundwater boreholes located outside the shallow thermal system (eg. #3858 near the junction of Broadlands Road and Centennial Drive) show no evidence of this decline and simply respond to rainfall recharge. The thermal borehole that is most affected by long term water level decline is in the Taupo golf course (#3857), although most thermal water bores between the AC Baths and Taupo Hospital, tapping into the upper aquifer, have shown some decline (eg. #3876, #3874). *Allis* (DSIR, 1988), first noticed a similar rate of water level decline in the north of Taupo by comparing spot measurements made in the 1970s and 1980s. Probable causes for this long-term water-level decline are: i) reduced mass recharge from deep aquifers as hot chloride water upflows were replaced by *steam;* ii) reduction in rainfall infiltration caused by urban development (storm water collection); iii) increased downflows from the upper aquifer to the underlying aquifer through internal flows in domestic boreholes or enhanced fracture permeability (tension cracks).

Two areas of anomalously large water level declines were also identified: one at the western edge of the upper aquifer near Hilltop School (38 m drop) and the other near Karamu Street, off Rifle Range Road (30 m drop between 1960 and 1987). Both are inferred to be caused by a retreat of the upper aquifer at its edges as bore water levels decline towards the deeper lake level aquifer. Between 1987 and 1994, the Karamu Street borehole water levels have been declining at about 1 m per decade. They also show a response to rainfall recharge, rather than lake level variations. Some of these marginal bores (#3878, #3851) recently rose in water level dramatically as rainfall recharge temporarily restored the upper aquifer. This also suggests that downflows are occurring from the upper to the lower aquifer, locally transmitting any dynamic changes in upper aquifer pressures. The water-level minima of most northern bores lag behind the rainfall minima by about 6 months. This further supports the suggestion that mid-winter spring flowrate minima are actually caused by summer rainfall minima, not winter drawdown from pumped wells.

As with the springs, borehole temperatures have shown some diverse trends with time (Fig. 3). In the vicinity of AC Springs, bore #3880 @SIR #296) has shown a continual heating trend from 1976 to 1994 at a rate similar to Otumuheke and AC springs (20°C per decade) from an original temperature of about 40°C. The delayed response of this borehole to the heating pulse that started affecting the springs at least a decade earlier is presumably a consequence of local permeability variations. Delays can be caused by progressive heating of multiple aquifers separated by conductively-heated aquicludes. A high temperature bore @SIR #100) at Cumberland Street, near the industrial area, initially rose in temperature to about 100°C (at 30 m depth) then after 1980 gradually dropped to about 85°C. Repeat temperature surveys of bores in the central residential area between Taupo View Road and Taharepa Road showed large temperature declines (up to 40°C) during the 1980s. Temperatures in this area now appear to have stabilised at about 50 to 60°C. By contrast, bores to the south and deep bores drilled into the lake level aquifer have generally maintained relatively stable temperatures (as has the Waipahihi source spring).

An explanation for these different temperature changes is that the thermal heating pulse, which was initially created by steam rising from a deep expanding steam zone created by Wairakei pressure drawdown, has varied in timing and location, because of variations in permeability and conductive heating effects.

After initial pressure drawdown at Wairakei in the late 1950s, the surface heat flow peak first occurred in the early 1960s at Karapiti ("Craters of the Moon"). Between 1974 and 1981 the "Pony Club" eruptions on Broadlands Road marked the arrival of the heat flow peak in the northern part of the Tauhara field. In the vicinity of the AC Baths, the timing of the heating pulse appears to have been locally affected by thermal lags or delays caused by secondary heating of overlying cooler groundwaters and conductive heating effects. In the central residential area the peak of the heating pulse appears to have now passed and a new balance between upflowing steam and inflowing cold groundwater has re-established. To the south, at Waipahihi and along the lake edge, there has been no evidence of any heat flow changes caused by deep pressure drawdown. This supports the postulate of a separate hydrological system.

3 3 Geochemistry

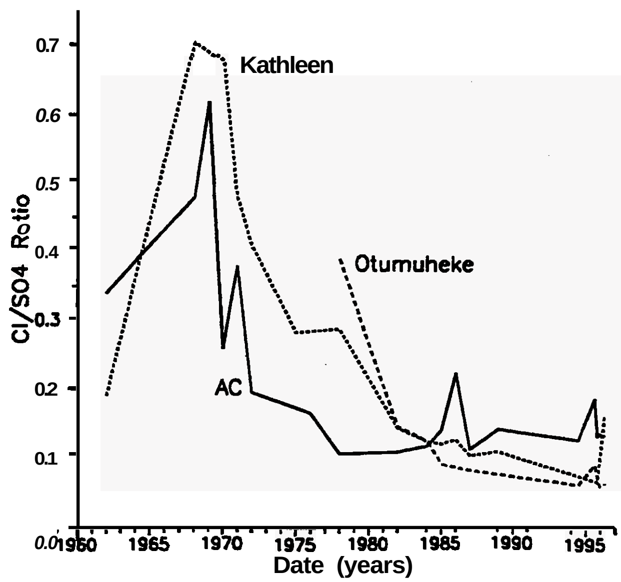


Fig. 4 - Cl/SO_4 ratios of northern Taupo springs.

This is particularly significant because it is diagnostic of an increasing contribution of steam-heated water. As steam rising from deeper aquifers is condensed into near surface water, H_2S gas is oxidised to H_2SO_4. The chemical changes at Otumuheke Spring (just 500 m north of Kathleen Spring) appear to have been delayed by about 5 to 10 years relative to the changes at Kathleen and AC springs. This is consistent with the delayed temperature effects from secondary steam heating.

Monthly monitoring during 1994 revealed variations in chemistry that are probably caused by changes in rainfall recharge to the shallow aquifer. The bicarbonates are the most variable (typically ±30%) because of the complex chemistry of dissolved CO_2 in groundwater. The sulphates vary by about ±10% as the oxidising environment for H_2S changes. The other major constituents (silica and sodium) vary by just a few percent in response to dilution effects.

The dilute chloride waters in the Waipahihi source area changed very little between 1962 and 1996 (Cl: 320 ±6% ppm, SO_4: 60 ±20% ppm, HCO_3: 380 ±20% ppm). In general, increased rainfall recharge which raises the thermal aquifer water level, causes increased flowrate (and temperature) and a *small* reduction in chloride.

An important observation from monitoring ten shallow Tauhara boreholes for chemical variation is that little change is observed in wells in the southern lake-level aquifer (containing dilute chloride water). Chlorides and sulphates are generally declining in northern Taupo bores but bicarbonates are increasing probably from diluting gas-enriched groundwater. Changes in atmospheric pressure appear to affect the gas chemistry of very shallow steam wells. Lower pressures result in larger steam flows, with lower entrained air (N_2) which affects the CO_2/H_2S ratio, because of reduced oxidation of H_2S. Two fumaroles that have been monitored (Hells Gate - Spa Park, and Pony Club) show recent increases in gas concentration, indicating that the steam is taking longer to reach the surface and more condensation is taking place. This may be diagnostic of a reducing upflux of steam and/or increased cooling from rainfall.

4. FUTURE IMPACTS

Future development of the Tauhara Geothermal Field for electricity production will require careful management of production and reinjection in order to minimise and mitigate any additional impacts on the shallow hydrology of perched thermal aquifers. Further drawdown of the steam zone pressure at the top of the deep geothermal aquifer would probably result in a continued reduction in steam flux to overlying aquifers, as has been experienced in recent years over much of central Taupo. Reinjection into this steam zone (using separated water) may help to locally restore chloride fluid upflows to pre-exploitation conditions (and even rejuvenate Spa Sights chloride springs) but could also reduce the surface steam flux and accelerate the recent temperature declines in most of the upper steam-heated aquifer. Deep production and reinjection (>800 m depth) appears to have the best chances of minimising further near-surface impacts. Initially, in an area of deep production, the additional drawdown of reservoir pressure could temporarily stimulate additional boiling and some enhanced upflow of steam to shallow aquifers, but this is unlikely to be as intense as the 1970s steam heating pulse, because the boiling would originate from a greater depth.

5. ACKNOWLEDGEMENTS

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