

REVERSIBLE AND IRREVERSIBLE CHANGES TO NATURAL THERMAL FEATURES DUE TO HUMAN ACTIVITY - SOME NEW ZEALAND EXAMPLES

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Abstract

Natural geothermal features, especially geysers, are sensitive to man made changes to their environment. Changes in level of the Waikato River at the Spa Sights, Taupo, due to operation of control gates on the river and lowering of the river bed, resulted in cessation of activity in the Waipikirangi and Crow's Nest geysers. Geysering was temporarily restored by "soaping" and changing the near surface plumbing of the geysers. Damming of the Waikato River and consequent formation of Lake Ohakuri led to flooding of parts of the Orakeikorako thermal area. Thermal features at low elevation were first stimulated and then drowned, whilst those at high level increased in activity. At Rotorua, removal of geothermal fluid by shallow domestic and commercial bores caused a decline in shallow pressures and in thermal activity at the Whakarewarewa Thermal Area. Since closure of bores within 1.5 km of the main geyser in 1986, pressures and some spring activity have increased.

Major development of the geothermal resource at Wairakei since the early 1950's progressively affected thermal features at Geyser Valley, Karapiti and finally the Spa Sights. In the main hot spring areas, the flow rates, chloride concentrations and spring temperatures decreased, and the periodicity of geysers increased. In the Karapiti fumarolic and solfataric area, steam flows increased initially then declined. The increase in steam flow was accompanied by more frequent hydrothermal eruptions.

History of the interaction of man and nature in New Zealand shows that some of the effects of development can be reversed if action is taken early, but large scale development is incompatible with the preservation of thermal features in their natural state. Specifically targeted reinjection may allow adverse environmental effects to be minimised.

1.0 INTRODUCTION

In this paper we deal mainly with changes that have occurred to natural thermal features due to other than deep production for electric power generation. Although there are over 20 geothermal fields with heat outputs between 100 and 400 MW(thermal) in the Taupo Volcanic Zone, New Zealand, only four have been noted for their outstanding geyser activity this century: Wairakei, Tauhara (including Spa Sights, Taupo), Orakeikorako, and Rotorua (Fig 1). We describe changes in these four areas and also changes to the Ohaaki Ngawha (hot pool) in the Ohaaki geothermal system (Fig 1). Geysers are the most sensitive of natural thermal features, and are often the first to exhibit the effects of natural- or human-induced pressure change in the geothermal system. We show that their behaviour can change in response to small increases or decreases in water level / pressure.

2.0 TAUHARA

Tauhara geothermal field is situated at the northern end of Lake Taupo, adjacent to and connected with the Wairakei field. In its natural state the field had three main areas of thermal activity: Spa Sights - the largest and most extensive area (Fig 2), a northern group of hot springs, and a southern group of hot springs. The main Spa Sights activity (approximately sixty features - Gregg and Laing, 1951) consisted of about three geysers, together with hot springs and mud pools, along a 400m stretch of the banks of the Waikato River

approximately 2 km downstream of the outlet of Lake Taupo. All, except six features, were on the right bank of the river, many close to river level. Named features included: Waipikirangi Geyser, Eunice Geyser, and Crow's Nest Geyser, and these were a major tourist attraction. Between 1931 and 1960 a number of events occurred which resulted in changes to these and other features, and their eventual demise. The changes in activity at Spa Sights have a number of causes.

2.1 Earthquake

On 3 February 1931 a large earthquake (magnitude 7.9) occurred having an epicentre near Napier, 90 km from Taupo. This was felt at Taupo with an intensity of 6 - 7 (MM) and caused cracking of the 2.4m high cone and upper portion of the vent of the Crow's Nest Geyser (Lloyd, 1957). The cracks allowed the hot water drain away, which temporarily destroyed the geysering activity. Extensive repair work was carried out by Mr Newdick, then proprietor of the nearby Spa Hotel, but this gave the cone a somewhat artificial appearance. However, it did not flow again until flood waters came down the river, at which time it overflowed and geysering recommenced. There are no reports of effects on other features at Spa Sights, by this earthquake.

2.2 Lowering of river level

In 1941, a dam with six regulating-gates was constructed at the outlet of Lake Taupo (TWN, 1941). Its purpose was to control the level of the lake and regulate the flow of the Waikato River to the (then) two hydroelectric power stations at Arapuni and Horahora. For the river to take the high flows the river bed at Totara Rapids, between Lake Taupo and Huka Falls and about 2 km downstream, was lowered by blasting (AJHRNZ, 1942). This resulted in a drop in river level of four to five feet (1.2 to 1.5m) at the thermal area (Lloyd, 1958). This had a major effect on the geysers: Waipikirangi Geyser ceased to play, Eunice Geyser played only intermittently, and Crow's Nest Geyser became dormant.

2.3 Artificial stimulation

Prior to the installation of the control gates, heavy rain had often caused the river level to rise. Mr Newdick built an artificial dam (about 1929) to enclose the basin of Waipikirangi Geyser (Lloyd, 1957). Through the dam an earthenware pipe was fitted which could be temporarily blocked, and then the water released to stimulate geyser activity.

Eunice Geyser was first recorded in eruption in 1937 by Mr Heath, then proprietor of the Spa Hotel. He and a Mr Fletcher noticed activity in the geyser, and conceived the idea of constructing a wall around the vent with sand bags so that when the river was in flood it would not flow into and submerge the geyser. Next morning the sand bags were lying on the edge of the river, proving that the geyser had erupted. They then constructed a more permanent rock and concrete dam with an opening that could be temporarily blocked with a sack (EFLloyd, pers comm.).

Mr E F Lloyd of the New Zealand Department of Scientific and Industrial Research (pers comm.) used carbide to stimulate action of Waipikirangi Geyser in the early 1950s.

Lloyd revived the Crow's Nest Geyser in 1953. He deduced that the dormancy of Crow's Nest was due to a drop in the local water table resulting from the permanent lowering of the river level (described above in section 2.2). He argued that if the Crow's Nest could be induced to discharge, the geyser would commence to erupt once again. He dug an open ditch so as to pierce the vent of the geyser about 30cm below the average level of the water in the vent. The result was that the Crow's Nest would erupt initially to 30 m, followed by displays of lesser height over a period of up to 1.5 hr. Lloyd (pers comm.) pierced the cone in two places: the lower hole had a valve on the pipe which was shut when the river level rose, to prevent the geyser being flooded. In these circumstances the water rose and flowed from the top vent and the geyser played. Eruptions continued at all but very low levels of the Waikato River, when the water in the vent receded below the lower outlet.

2.4 Short term natural variations.

In January 1953, geothermal features close to the river suddenly increased in activity; this was associated with the high level of the river after recent rain (NZH, 1953). The Waipikirangi Geyser played again after seven years, erupting 15m into the air, and nearby Eunice Geyser increased its activity to one eruption every four to six hours, after years of intermittent playing. Twenty or more small geysers and boiling pools came into noisy life. The Crow's Nest Geyser, the most famed geyser, remained quiet although there were signs of activity at the bottom of the crater.

2.5 Development of Wairakei Geothermal Project

Development of the Wairakei Geothermal Power project started in 1950 and significant discharge of the wells began in 1952. This had an almost immediate effect on the natural activity in the nearby Geyser Valley (see below), and by 1954 the Great Wairakei Geyser had been reduced to a steaming pool (RDP, 1955). However, at the Spa Sights, Waipikirangi was erupting strongly in late 1958 (RDP, 1958). Eventually the pressure drawdown (described later) reached the Spa Sights and all the deep seated springs here ceased to flow and the water levels disappeared from sight.

3.0 ORAKEIKORAKO

The hydrothermal area of Orakeikorako (Fig 1) is situated on about 1.5 km of both banks of the Waikato River 37 km SSW of Rotorua. Hochstetter (1864) described the area in the following terms:- *“Along its banks rise white steam clouds from hot cascades falling into the river and from basins full of boiling water surrounded by white masses of rock. There, a steaming fountain rises on high, which sinks back again, and now a second fountain rises up in another place, then this ceases also, while two start to play at the same time, one right under the river bank, the other opposite on a terrace, and thus the play changes continually as if an artistic and mighty water works were being tested to check whether all the fountains were in working order and the cascades had sufficient water. I tried to count all the separate places where a basin of boiling water was visible, or where a steam cloud indicated that one was present. I counted 76 points, without, however, being able to view the whole area.”* Lloyd (1972) recorded the location of over 1000 thermal features including 88 geysers.

The Waikato River flowed in a narrow channel through the area until January 1961 when the valley was flooded to a depth of 18 m by the lake formed behind the newly constructed Ohakuri Dam, situated about 8 km downstream. The lake began rising at Orakeikorako on 21 January 1961 and attained the final level of 289.6m a.s.l. on 8 February 1961. Lloyd (1972) reported detailed observations on the changes in water levels, temperatures and activity of the springs and pools, particularly those springs emerging below 291.1m a.s.l. Observations on an assemblage of flowing and non-flowing springs along a line normal to the valley provided a profile across the water table. The temperature, discharge, and chloride and ammonium content of selected springs were measured. Most observed changes resulted from the raised water levels, and were grouped under three headings: (1) changes to springs submerged by the rising lake, (2) changes attributed to increased hydrostatic pressures in the hydrothermal system as a result of the lake formation, and (3) long-term changes as ground water levels in the country rose to a gradient controlled by the level of the new lake.

3.1 Springs submerged by the rising lake

Lloyd (1972) observed that as the lake level rose, non-flowing springs began to erupt, hot discharging springs increased in heat flow and temperature, boiling springs increased in temperature and began geysering, and dormant geysers were reactivated. The most interesting observations were on Spring N85/8/522, a fumarole: this went through the full sequence from fumarole to geyser to flowing spring. When the lake rose to 1.4m below the fumarole it became a geyser, erupting at 10 minute intervals: each eruption ejected water to 2.4m. As the water level rose the period gradually decreased until the lake level was 0.45 m below the spring orifice, at which point geyser action ceased; the spring was boiling continuously to 0.6 m high, and

discharging a stream of water at 5 *Us*. Lowering of the overflow level (equivalent to raising the lake level) caused vigorous boiling to cease, and raising the overflow level (equivalent to lowering the lake level) 0.45 m above normal caused boiling and true geyser eruptions to recommence. Thirteen spring waters were analysed daily during lake filling and, except in those from Wainui Geyser, their mineral content did not change significantly. Chemical dilution changes were observed in Wainui Geyser, which was located in intensely fissured ground. This apparently allowed lake water to enter the hydrothermal system. Activity ceased in all these features when finally flooded.

3.2 Effect of increased hydrostatic pressure of lake water

Hot springs that remained above the lake level were able to be observed over a longer time period; they showed similar changes to those that were submerged. The spring named "Map of Australia" discharged 0.4 l/s in 1959. By 3 February 1961 the flow averaged 0.9 *Us*, and two days later was 1.2 *Us*. The following day, the gradual increase in heat output culminated in an eruption of massive water domes to a height of 1 m, accompanied by localised earth shocks, and the discharge exceeded 15 *Us*. On 7 February 1961, eruptions ceased and the flow was less. A new steady state was reached in early 1962, with both water levels and temperatures exceeding those measured before lake filling (flow = 1.4 *Us*). The chloride content of the spring waters did not change, but a decrease in the ammonium ion preceded the reduction in activity, which was interpreted as being caused by a decrease in steam available to heat the waters (Lloyd, 1972). Approximately 75% of the springs at Orakeikorako were submerged by Lake Ohakuri (Lloyd, 1972).

There are no plans to restore the river to its former level, but even if there were the long time since the thermal features were submerged (36 years) would probably preclude the natural restoration of the features.

3.2 Long term changes

During the second week of February 1961, hot water began escaping from many points along the lake edge and during the following two months also emerged from seeps and small springs at progressively higher elevation. The water table continued to rise, as seen by high water levels in hot springs, rejuvenation of existing springs and outbreaks forming new features. The surge in abnormal activity slowly progressed inland from the lake: rising water levels were first evident near the lake shore in February 1961, reaching a peak at the base of the Rainbow Terrace by November 1961; at the base of the Golden Terrace they were first evident in March 1961 and rose to a peak in July 1962; on Artist's Palette they were first evident in June 1962 and continued to rise through 1963. The rate of rise bore a direct relation to rainfall (Lloyd, 1972). Latest data (Cody, pers comm.) indicate that in 1996-97 there are at least 30 geysers active.

4.0 ROTORUA

Rotorua geothermal field (Fig 1) is situated beneath Rotorua City near the southern end of Lake Rotorua and, as defined by surface activity and shallow drillholes, covers an area of about 12 km² (Wood, 1992). The deep system has a shallow outflow from upwellings, mainly in the south near the Whakarewarewa Thermal Area and south-east at Ngapuna, which flow north and north-west towards Lake Rotorua (Glover, 1967, Stewart et al 1992). About 540 thermal features (including hot springs, hot pools, mud pools, geysers and steam vents) were surveyed between 1976 and 1969 (Lloyd, 1975), and are a major tourist attraction.

The first geothermal wells in Rotorua were drilled in the 1920s, but from the early 1960s wells were drilled with ever increasing frequency. By the mid-1980s, about 750 shallow wells were drilled (>95% are <200 m depth) and activity of the features had declined to an all time recorded low (Cody and Lumb, 1992). The waning of natural surface activity, in particular the geysers and hot springs at Whakarewarewa Thermal Area in the late 1970s and early 1980s, prompted the fear that Pohutu Geyser (the main geyser) might be lost. A government-funded monitoring programme was initiated in 1982 and by the end of 1985 conclusive evidence was obtained to confirm the decline of pressures and natural activity. The programme established that the winter daily mass discharge from shallow domestic wells was around 3 l kt/d (Timpany, 1990), equivalent

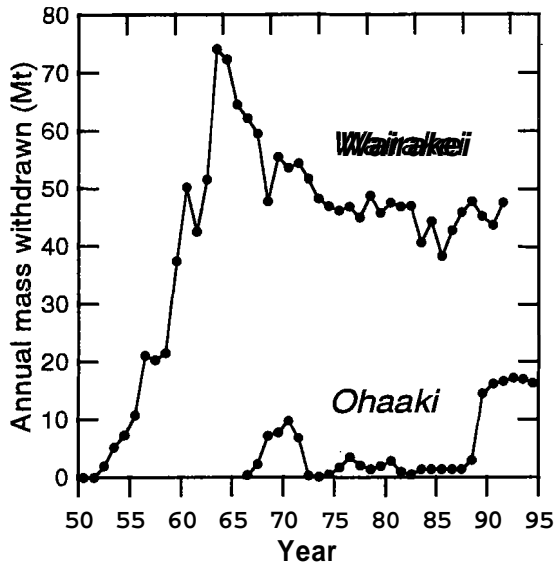


Figure 4. Annual mass withdrawal from Wairakei and Ohaaki fields.

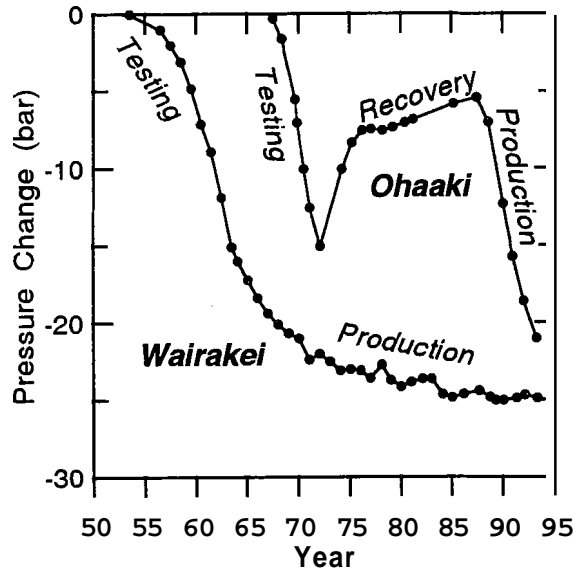


Figure 5. Pressure drawdown in Wairakei and Ohaaki fields.

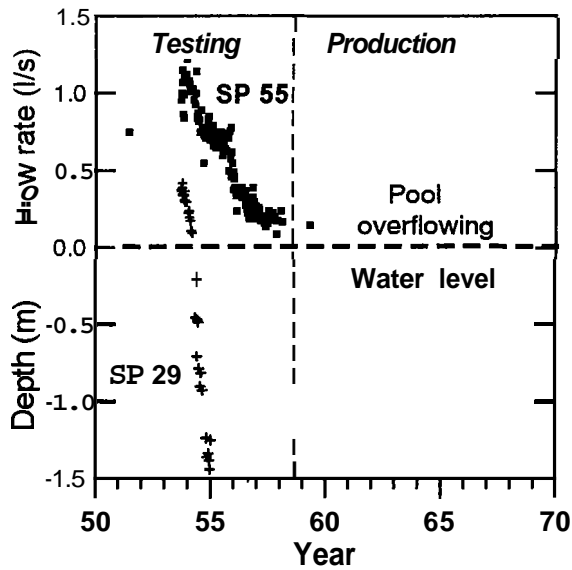


Figure 6. Changes in flow rate and water level in hot springs at Wairakei.

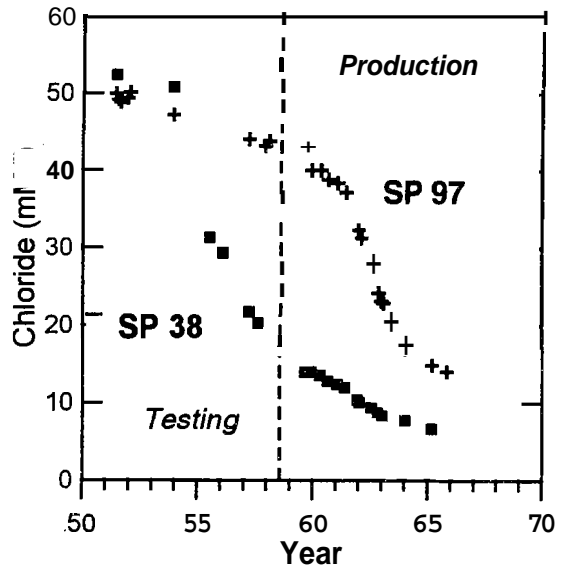


Figure 7. Changes in chloride content of water in hot springs at Wairakei.

to about 40% of the estimated natural deep upflow of the Rotorua system and about 25% of the current withdrawal from Wairakei (see below). In 1986, a government-initiated bore closure programme and a charging regime for discharging wells was implemented. By late 1992, only 141 wells remained which were producing 9.5 kt/d, with 5.1 kt/d being reinjected (Grant-Taylor & O'Shaughnessy, 1992).

A network of monitor (M) wells was set up in 1982. These were located throughout Rotorua City and were generally 80 - 180 m deep. Prior to the bore closure programme, the M wells showed a rise in pressure (water level) in summer when the well discharge was low, and a drop during the winter months when the total withdrawal from the system was greatest. M6 and M16 are typical wells and a time-series plot of their water levels shows a rise of about 2 m soon after the bore closure programme was implemented (Fig. 3).

Since the bore closures began, the following have also occurred (Scott and Cody, 1997; Cody, pers comm.):

- The three springs, Parekohoru, Rachel, Kuirau Lake have increased in activity.
- Kereru Geyser, which became dormant in 1972, recommenced eruptions in January 1988.
- Okainga Geyser, which did not erupt during the late 1970s and early 1980s, has been reliably erupting every 25 - 35 minutes since 1992.
- Water levels have risen in the vents of Waikite and Wairoa geysers, but eruptions have not recommenced.
- Pohutu Geyser, which has had progressively more frequent but shorter duration eruptions in the 1950s - 1980s, was in continuous eruption for 9 hr in July 1997.
- Waikorohihi and Mahanga geysers have increased in frequency and power of eruption since about 1990

However:

- Te Horu Geyser, which ceased erupting in 1972, had not resumed by February 1997.
- Eruptions from Papakura Geyser, the cessation of which (in 1979) was responsible for the initiation of the monitoring programme, have not recommenced.

The Rotorua experience shows that geothermal development on even a relatively small scale can have a deleterious effect on natural springs and geysers. However, the large reduction in bore discharge since 1986 has resulted in *some* of the features recovering, but others still remain "dormant".

5.0 WAIRAKEI

5.1 Development History

At Wairakei, exploratory drilling began in 1950 and 69 prospecting holes had been drilled and tested by December 1958. During this "Test Discharge Period" mass withdrawal increased to about 20 Mt/yr (about 5.5 kt/d). During commissioning of the Wairakei Power Station (November 1958 to October 1964), **annual** mass withdrawal rose to 75 Mt/yr, after which it declined and **has** remained at about 45 Mt/yr since 1975 (Fig 4).

Prior to development the reservoir was liquid-dominated, with fluid at or near boiling point for depth. A thin 2-phase zone existed in the upper part of the reservoir (Grant and Home, 1980), overlain by a zone of cold ground-water which was locally heated by fluids escaping upwards to supply natural thermal features at the surface. By 1958, the cumulative mass withdrawal was about 88 Mt, resulting in deep-liquid pressures decreasing by about 3 bar (Grant pers comm., in **Garg** and Rice, 1979). During the early stages of production (1960s), large pressure decreases extended across most of the field leading to expansion (both vertical and horizontal) of the 2-phase zone, and formation of a vapour-dominated zone in the upper **part** of this zone. By the mid-1970s deep liquid pressures had settled at about 25 bar below pre-production values (Fig 5).

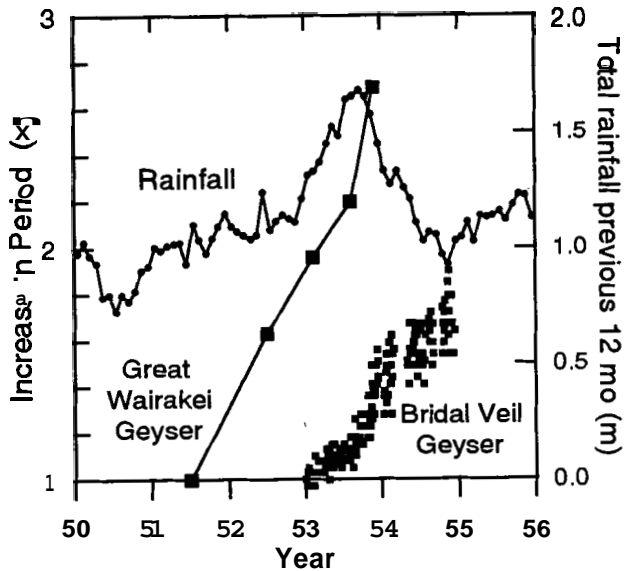


Figure 8. Changes in eruption period of geysers at Wairakei during field testing. Note, increases cannot be caused by decrease in rainfall.

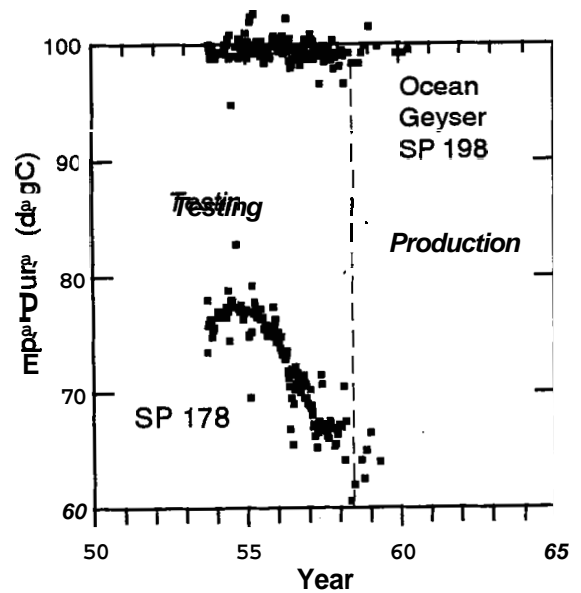


Figure 9. Changes in outflow temperature of hot springs at Wairakei during field testing and early stages of production.

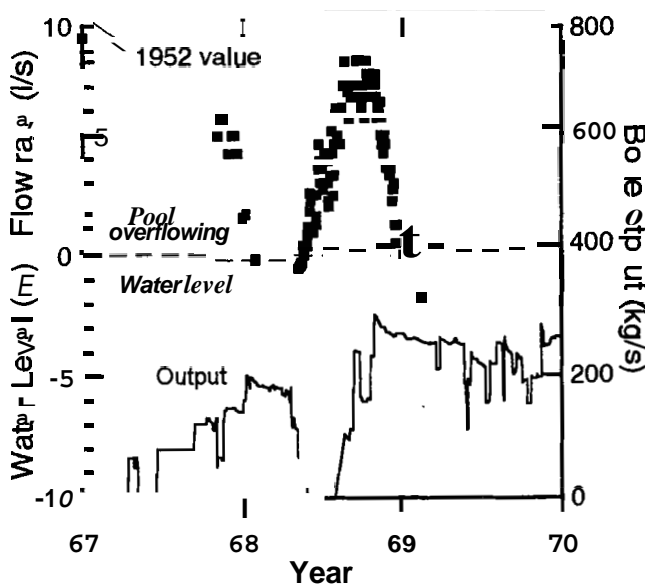


Figure 11. Changes in overflow rate and water level of Ohaaki Pool caused by changes in output from nearby bores.

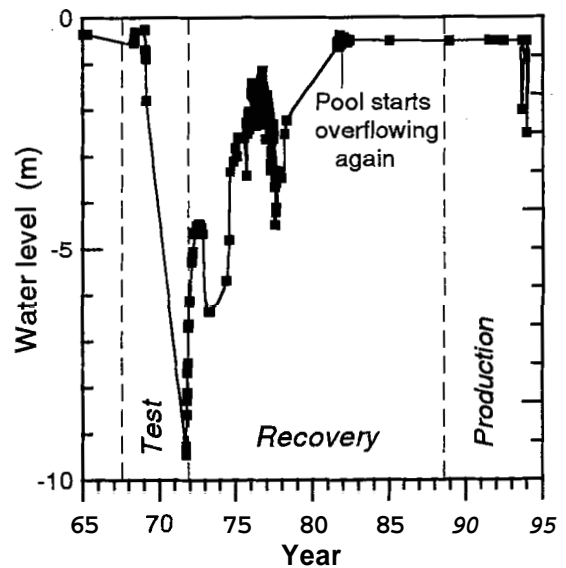


Figure 12. Changes in water level of Ohaaki Pool. Compare with pressure changes in Figure 5.

5.2 Impact of Development

Prior to development, Wairakei was a major tourist attraction noted for a wide variety of **natural** thermal features which included about 20 geysers, fumaroles, hot springs, hot pools, and sinter slopes (Wilson, 1976), and over 700 features were catalogued (Gregg and Laing, 1951).

Regular observations and measurements of selected features started in November 1952, *after* exploratory drilling and well discharges had begun. Initially, the changes to the natural features were small and isolated and thought to be caused by natural climatic variations. **This** was, in part, because some features changed during the testing period whilst others did not show any change. At that time, the conceptual model of the geothermal system envisaged that any fluid withdrawn from the upper part of the reservoir would be rapidly replaced by hot fluid from deeper in the reservoir, and that **natural** features would be unaffected (Wilson, 1976). It is now recognised the thermal features were fed by fluids escaping from the upper part of the reservoir, along faults or fissures. Withdrawal of fluid from the upper part of the reservoir through production bores, and concomitant pressure decrease, led to a decline in the amount of **this** fluid feeding the features. This decline caused (Glover and Hunt, 1996):

Decrease in flow rate from springs and pools. Measurements show that there was a decrease in flow rate from many springs in Geyser Valley at Wairakei during the Test Discharge Period. One example is Waitangi Pool (SP55): in November 1953 the outflow rate was about 1.2 l/s, which decreased to about 0.2 l/s in late 1957 (Fig 6). Another example is Spring 29: in November 1952 this discharged periodically, but in October 1953 the periodicity ceased, and the rate of discharge steadily declined until April 1954 when discharge ceased (Thompson, 1957). The water level then fell to 1.5 m below the edge, at which point measurements could no longer be made (Fig 6).

Decrease in chloride content of fluids from springs. Prior to exploitation, fluids in the upper part of the Wairakei reservoir had a chloride content of about 47.5 mM/l (1680 mg/kg, at 265°C, and enthalpy of 1160 kJ/kg; Brown et al., 1988) which after adiabatic steam loss would have a content of about 70.9 mM/l (2506 mg/kg) at 99°C at the surface. Most fluids emerging from the natural features had a chloride content of about 45 - 50 mM/l (1600 to 1775 mg/kg), indicating some dilution by near-surface warm (150°C) water containing 8.5 mM/l (300 mg/kg) chloride (Brown et al., 1988). As the deep pressures declined so did the chloride of the emerging waters, indicating increased dilution of the upflowing deep water by the near-surface groundwater. Many springs in Geyser Valley showed rapid decreases in chloride content during the Test Discharge and early part of the Production Periods (Fig 7). The chloride content of Spring 38 (Dragon's Mouth Geyser) declined from about **50** mM/l in 1951 to about 20 mM/l in 1957 (Fig 7); a decrease of more **than** 50%. In general, the springs at the highest elevation showed the quickest change (Glover and Hunt, 1996). Springs at lower elevations had larger flow rates and the smallest change during the Test Discharge Period. For example, in Spring 97 (Champagne Cauldron) the chloride decreased by only about 20% during the Test Discharge Period (Fig 7). However, during the early 1960s the chloride content decreased from about 40 mM/l to about 15 mM/l in 3 years.

Increase in eruption period of geysers. The Bridal Veil Geyser (SP 199), in Geyser Valley, was monitored closely for 2 years during the Test Discharge Period. The eruption period (time between the **start** of successive eruptions) increased from about 38 min. in November 1952, to about **55** min. in December 1953 and to about 65 min. in December 1954 (Fig 8). The eruption period of the Great Wairakei Geyser increased from about 12 to more than 30 hours (Glover and Hunt, 1996), before the feature died in 1954.

Decrease in temperature of hot pools and springs. The temperature of some hot springs and pools at Wairakei declined by up to 20°C during the Test Discharge Period; these include the Waitangi Pool and SP178 (Fig 9). However, the temperature of other features showed little change during this time: these included Ocean Geyser (Fig 9). These features maintained temperatures near boiling, while flow rates decreased significantly, because the fluids were diluted by warm (>100°C) low chloride water (Glover and **Hurt**, 1996).

Change in heat flow. At Wairakei there have been large, but, localised, changes in surface heat flow associated with exploitation (Allis, 1981). Increases and decreases occurred during the Test Discharge Period. In Geyser Valley the heat flow reaching the Wairakei Stream decreased steadily from 52 MWt in 1952 to 30 MWt in 1958, and to 5 MWt in 1966 when measurements ceased (Glover, 1977); this reflected a decline in the natural thermal features. However, expansion of the 2-phase zone resulted in a rapid increase in steam flow at the Karapiti Thermal Area, resulting in an increase of fumarolic activity and hydrothermal eruptions. Surface heat flow increased from 40 MWt in 1950 to 90 MWt in 1958. After large scale production began the heat flow increased rapidly to a peak of 420 MWt in 1964 and then declined to about 220 MWt (1979-88) (Fig 10). Hydrothermal eruptions from craters up to 25 m diameter continue to occur every 1 - 2 years (Fig 10) and fumarolic activity continues. The area is now a major tourist attraction.

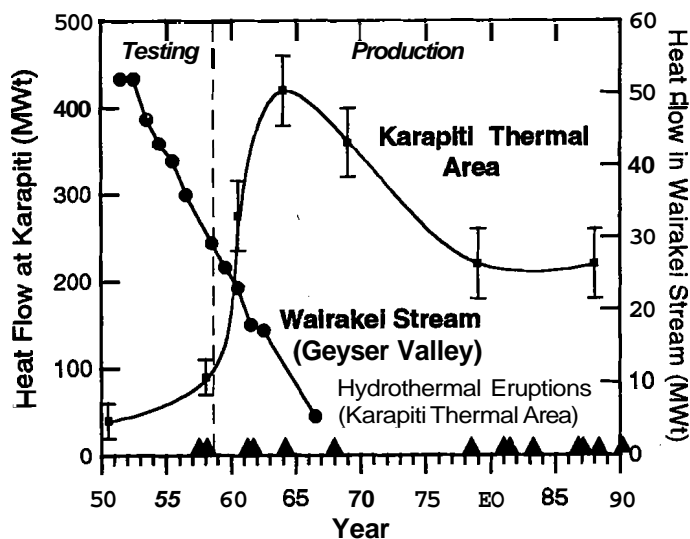


Figure 10. Changes in heat flow from the Karapiti Thermal Area and in Wairakei Stream, at Wairakei. Also shown (as solid triangles) are the times of hydrothermal eruptions in the Karapiti Area.

6.0 OHAAKI

6.1 Field Development history

At Ohaaki (Broadlands) field, exploratory drilling began in 1965, and 25 deep wells had been drilled by 1971. From mid-1967 until the end of 1971, test discharges were conducted during which time the annual mass withdrawal rose to about 10 Mt/yr (Fig 4); during this "Test Discharge Period" all the fluid withdrawn was discharged into the Waikato River. In the following 16 years, a further 18 holes were drilled but no extensive testing was done; the average mass discharge was only 1.5 Mt/yr and did not exceed 3.5 Mt/yr. This time is known as the "Recovery Period". Commissioning of the Ohaaki Power Station (116 MWe installed capacity) began in August 1988 and was completed in November 1989. Mass withdrawal rose to 16.2 Mt/yr in 1990 and has remained at similar values since then (Glover et al, 1996). Since commissioning the power station about 60% of the fluid withdrawn has been reinjected; the remainder (about 6 Mt/yr) has been discharged to the atmosphere. Deep-liquid pressures decreased by about 15 bar during the Test Discharge Period, but subsequently recovered by about 10 bar during the Recovery Period before decreasing again after production began (Fig 5). During the testing and early stages of production the pressure changes at Ohaaki (15 bar) were much greater than at Wairakei (3 bar), although the mass withdrawal rates at Ohaaki were smaller than at Wairakei (10 and 20 Mt/yr respectively).

6.2 Impacts of development

Prior to exploitation the Ohaaki field had few natural thermal features (cf. Wairakei). The largest and most significant feature is the Ohaaki Pool, a boiling pool (750 m² area) which in its natural state had a surface discharge of about 9 l/s. During the Test Discharge Period at Ohaaki, outflow from the pool decreased when nearby wells (BR 2, 3, 4, 8, 11) were discharged (Glover et al, 1996), recovered when the discharges were

temporarily stopped, and decreased again when the bores were reopened (Fig 11). By late 1968, overflow had ceased and the level in the pool fell rapidly. At the end of the Test Discharge Period the pool was empty. During the Recovery Period the water level rose and the pool began to overflow again, assisted by the addition of separated bore water (Fig 12). The chloride content of the water was very constant (about 1060 mg/kg) during the fluctuations of flow and water level, but increased with the addition of the bore water. However, the level of the pool fell again when production began in 1988. Subsequently, remedial work was undertaken which included sealing the base of the pool with 600 m³ rock and gravel which was then capped by a layer of reinforced concrete layer. Water now flowing through the pool is hot (160°C) separated bore water.

7.0 CONCLUSIONS

- Deleterious changes to natural thermal features have resulted from a variety of human activities, including: altering river levels (excavations, damming), draw-off of shallow, geothermal waters (without reinjection), and draw-off of deep fluid (with and without reinjection).
- Geysers and hot springs are very sensitive to such human activities.
- In some cases, thermal features which have been **affected** have been rejuvenated after stopping or minimising the human activity, however, recovery times may be long (>10 yr.).
- Current conceptual models suggest that once a feature has died as a result of human activity, there is little chance of it naturally rejuvenating without assistance.

The attrition of natural geothermal features resulting from human activity **has** caused public concern in New Zealand, and is an impediment to further developments, even in fields containing what were formerly considered to be minor thermal features. Developers need to be sensitive to this concern, and clearly address possible impacts and their mitigation during the permitting process. Further research work needs to be undertaken to establish the critical parameters causing changes to thermal features, and devise methods to minimise the changes.

8.0 ACKNOWLEDGEMENTS

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