EXAMPLES OF ENVIRONMENTAL CHANGES

No significant development of a high-temperature geothermal field has taken place without some environmental changes having occurred. Some well-documented examples are given here.

1. CHANGES AT WAIRAKEI GEOTHERMAL FIELD (NEW ZEALAND)

Wairakei field is situated in the central volcanic region of New Zealand. Exploration began in 1949, and the first exploration drillhole was drilled in 1950. Initial exploration holes were shallow (<300 m) but successfully encountered high temperatures which led to more and deeper holes being drilled. By December 1958, 69 prospecting holes had been drilled and test discharged. During this "Test discharge period", mass withdrawal increased to about 20 Mt/yr. The Wairakei power station (original installed capacity 192.6 MWe) was progressively commissioned from November 1958 to October 1964, during which time the annual mass withdrawal increased to 75 Mt/yr, after which it declined and has remained at about 45 Mt/yr since 1975 (Figure 3). The time since November 1958 is referred to as the "Production period".

Prior to development of the field, the reservoir was liquid-dominated with fluid generally at or near boiling point for depth and a thin 2-phase zone existed in the upper part. Over-lying the reservoir is a zone of cold groundwater, locally heated by fluids escaping upwards to supply natural thermal features at the surface.

At the time of its planning and exploration, environmental concerns were regarded as relatively unimportant and no serious environmental problems were foreseen. However, during the late stages of construction some environmental issues arose, but by that time there had been a large capital expenditure, a large labour force was working, and the reasons for the environmental changes were equivocal so development proceeded. In later years the environmental effects and their causes have become clearer.

1.1 Pressure changes

Withdrawal during the test discharge period resulted in deep-liquid pressures decreasing by about 3 bar
(0.3 MPa). However, this value must be treated with caution because some of the data were not obtained by direct down-hole measurements but calculated from well head pressures in wells standing shut and full of water. During the early stages of production (1960’s), large pressure decreases extended across most of the field leading to the expansion (both vertical and horizontal) of the 2-phase zone, followed by the formation of a vapour-dominated region in the upper part of this zone. By the mid-1970’s deep-liquid pressures had settled at about 25 bar (2.5 MPa) below pre-production values (Figure 3).

### 1.2 Changes to natural thermal features

Prior to development, Wairakei was a major tourist attraction noted for a wide variety of natural thermal features which included geysers, fumaroles, hot springs, hot pools, and sinter slopes. Most of these features were located in two adjacent valleys: Geyser Valley (Wairakei Stream) and Waiora Valley (Kiriohinekei Stream) (Figure 4). Exploratory drilling began in the Waiora Valley, and it was here that most production wells were located; no wells have been drilled in the Geyser Valley.

Regular observations and measurements (flow rate, chloride content and temperature) of selected thermal features did not begin until November 1952, after exploratory drilling and well discharges had begun. Initially, the effects of mass withdrawal on the natural features were small and isolated, and were thought at that time to be caused by natural climatic variations. This was, in part, because the data showed that although some features changed during the testing period, others did not show any change. Following the large increase in mass withdrawal after commissioning, most features in Geyser Valley died and those that did not were severely reduced. This rapid decline of the thermal features came as a surprise to many people.

Measurements made during the test discharge period and early part of the production period show that the main changes to the natural thermal features before their death were the following.

**Decrease in flow rate from hot springs and pools**

Measurements show that there were large decreases in the flow rate from many hot springs and pools in Geyser Valley during the test discharge period. Examples are shown in Figure 5. At Waitangi Pool (SP55) in Nov. 1953 the outflow rate was about 1.2 l/s, which decreased to about 0.2 l/s in late 1957. Another example is Spring 29, in Nov. 1952 this discharged periodically, but in October 1953 the periodicity ceased, and the rate of discharge steadily declined until April 1954 when the discharge ceased. The water level then decreased until it was 1.5 m below the edge, at which point measurements could no longer be made (Figure 5). These changes occurred as a result of pressure drop of less than 3 bar (0.3 MPa) in the
Decrease in chloride content of springs

Prior to exploitation, fluids in the upper part of the Wairakei reservoir had a chloride content of about 1680 ppm (265°C, enthalpy 1160 kJ/kg; Brown et al., 1988) which, after adiabatic steam loss, would have a content of about 2506 ppm (99°C) at the surface. Most fluids emerging from natural features at Wairakei had a chloride content of about 1600-1700 ppm, indicating some dilution by warm (150°C) near-surface groundwater containing about 300 ppm chloride (Brown et al., 1988).

Many springs in Geyser Valley showed rapid decreases in chloride content during the test discharge period and early part of the production period (Figure 6). The largest (measured) decreases in the test discharge period were at Springs 18 and 38 (Dragon's Mouth Geyser), where the chloride content declined from about 1800 ppm in 1951 to about 700 ppm in 1957 (Figure 6); i.e. a decrease of more than 50%. In general, the highest (topographically) springs showed the earliest change. Springs which were at lower elevations, and had larger flow rates, had the smallest change during the test discharge period. For example, in Waitangi Pool (Spring 55) the chloride decreased by only about 20% during the test discharge period (Figure 6), but during the early 1960s the chloride content decreased from about 1500 ppm to about 500 ppm in 3 years.
Increase in eruption period of geysers

Little quantitative data are available about the decline of the geysers at Wairakei. It is known that the eruption period (time between start of successive eruptions) of two geysers increased during the Test discharge period, before geysering ceased. The eruption period of Bridal Veil Geyser (Spring 199) increased from about 38 min. in Nov. 1952, to about 55 min. in Dec. 1953, to about 65 min. in Dec. 1954 (Figure 7). Another example is the Great Wairakei Geyser (Spring 59): during the test discharge period the eruption period increased from about 12 to more than 30 hrs, before the feature stopped geysering in 1954 (Figure 7). Comparison of the eruption period data with rainfall measurements (Figure 7) shows that the increases in period were not caused by a decrease in rainfall. Similarly, the reductions in flow rate from springs could not have been caused by changes in rainfall.

Decrease in temperature of springs and pools

Some hot springs and pools at Wairakei showed outflow temperature declines of up to 30°C during the Test discharge period: these included SP18 and SP178 (Figure 8). However, the temperatures of some other features in Geyser Valley showed little change: these included Rainbow Pool (SP197) and Ocean Geyser (SP198) (Figure 8). These features maintained temperatures near boiling, while flow rates decreased significantly, because the upflowing geothermal fluids were diluted by warm (>100°C) groundwater.
Lecture 2 Examples of environmental changes

FIGURE 7: Changes in length of eruption period ($T/T_0$) of geysers in Geyser Valley at Wairakei during the test discharge period; periods are normalised to $T_0 = 12.5$ hours for Great Wairakei Geyser, and 39 min for Bridal Veil. Rainfall data are monthly running totals of rainfall in previous 12 months. Note the steady increase in length of eruption period with time.

FIGURE 8: Changes with time in temperature of water in thermal features at Wairakei geothermal field, as a result of development; note the different behaviours – the temperature in some features remained near-constant, while in others it fell; taken from Glover & Hunt (1996)
1.3 Groundwater level changes

A cold groundwater zone overlies the reservoir, and extends from near the surface (5-30 m) to several hundred metres depth. The zone consists of several aquifers (some perched) in which water may be flowing laterally in response to topographic relief or geological control.

Groundwater levels have been monitored in shallow (20-50 m depth) holes since 1953. In most places the water level has varied by about ±1 m in response to seasonal variations in rainfall (for example 34/0, Figure 9). However, in monitor holes in an area adjacent to the Western borefield the levels have fallen significantly. These holes are situated near a region of cold water invasion, and it is believed that a large part of the cold downflow consists of water from the groundwater zone. The largest and best-documented change has been at hole 14/0, where the level is now about 30 m below that in 1953 (Figure 9). In the late 1970’s it was realised that a significant part of the downflow was associated with vertical flows in non-producing wells that had damaged or broken casing. These breaks were sealed off, reducing the downflow from about 200 to about 100 kg/s.

1.4 Groundwater temperature changes

The temperature of water in the groundwater monitor holes (at or near the groundwater surface) has been measured since the mid-1950’s, but not as frequently as the levels. Temperature measurements are less reliable and more variable than level measurements because of difficulties inherent in measuring temperature, water level changes and steam heating effects, as well as short-term climatic effects.

In monitor holes away from natural thermal features and outside production areas, the groundwater temperature has remained cold (Figure 10).
Before production started, groundwater temperatures in the main part of the Eastern borefield varied from ambient to about 75°C (Figure 11). After production began, the temperatures in wells near the centre of groundwater decline rose by up to 60°C (Wk 14/0; Figure 11) due to steam heating and groundwater level decline. In wells further away from the centre of decline (e.g. Wk 37/0), the temperature rise was correspondingly less. Since the 1980’s, groundwater temperatures here have remained constant at around 70-80°C.

1.5 Changes in surface heat flow

At Wairakei, there have been large but localised changes in surface heat flow associated with exploitation (Allis, 1981). Changes, both increases and decreases, occurred during the test discharge and production periods. In Geyser Valley the heat flow reaching the Wairakei Stream from springs and geysers decreased steadily from 52 MWt in 1952 to 30 MWt in 1958, and to 5 MWt in 1966 when measurements ceased; this decrease reflecting the decline of the natural thermal features. In the Karapiti thermal area, an outbreak of fumarolic activity and hydrothermal eruptions began in 1954, and the heat flow increased from 40 (1950) to 90 MWt (1958). Measurements at Karapiti showed that after production began the heat flow there increased rapidly to a peak of 420 MWt (1964) then declined to about 220 MWt (1979-88) (Figure 12). This increase resulted in an expansion of the area of thermal ground, which caused trees and other temperature-sensitive vegetation to die. However, it also allowed some rare species of thermophilic vegetation (mosses, shrubs) to capitalise on the expansion of thermal area. Hydrothermal eruptions from craters of up to 25 m diameter occur spasmodically every 1-2 years (Figure 12), and fumarolic activity continues. The centres of thermal activity appear to migrate randomly. The area is now a major tourist attraction, but the thermal features are insignificant compared with that of Geyser Valley before production began.
1.6 Ground movements

Ground movements have occurred at Wairakei as a result of mass withdrawal. Vertical movements, in the form of subsidence, have been the largest and are amongst the greatest induced subsidences in the world.

Vertical movements

At Wairakei, subsidence was first detected in 1956, and led to the installation and regular relevelling (to 2nd order standard) of a network of benchmarks. The relevelling data have shown that subsidence has occurred over most of the production field but is greatest in the eastern part of the field where it is centred about 500 m northeast of the Eastern borefield (Figure 13). The subsidence rate in the centre reached about 480 mm/yr in the 1970’s but has since declined to about 215 mm/yr, and the total subsidence there now exceeds 15 m (Allis, 2000). The longest record is for benchmark A97, situated in the Eastern borefield, where subsidence is now about 4 m. The data (Figure 14) shows that subsidence began during the test discharge period, but did not exceed 25 mm/yr until after commissioning when it rapidly increased to about 145 mm/yr. Although the pressure decline stabilised in the mid-1970s, the subsidence rate did not start to show a reduction until the late 1970’s. The maximum subsidence in the main subsidence bowl is predicted to increase to about 20 m by the year 2050 (Allis & Zhan, 2000)

The principal environmental effect of the subsidence has been a change to the profile of the bed of the Wairakei Stream as a result of differential subsidence: once a fast flowing narrow stream, it now has a pond in the area of maximum subsidence. This pond is up to 6 m in depth, and the bottom is filling with silt. Trees that have been flooded have died; but the pond has become a popular habitat for water birds. The subsidence has caused casing damage in wells closest to the main subsidence area: compressed joints and breaks occur at 140-270 metres depth, which defines the vertical section of compaction (Bixley and
Hattersley, 1983). There has been no casing protrusion because the wells are adequately cemented near the surface, and so the compression is manifested at depth by casing deformation.

**Horizontal movements**

At Wairakei, horizontal ground movements were first suspected in 1964, and this was confirmed early in 1965 by measurements along the main steam lines. Subsequent measurements have shown horizontal movements of more than 100 mm/yr and tilting rates of more than 1 microradian/yr (Allis, 1990).

Data suggest that in the area of greatest subsidence there is a zone of compressional strain (buckling of pipes) which is surrounded by an annulus of tensional strain (ground surface cracking). Fissures have opened up in some of the surrounding fields, but are soon filled with soil carried in by heavy rainfall. Tensional cracking has damaged the surface along a 500 m section of nearby state highway 1 (Figure 13), necessitating rebuilding and resurfacing. The horizontal strains have also necessitated mounting pipelines on sliding foundations and insertion and removal of sections of pipelines in the Eastern borefield.

### 2. CHANGES AT OHAAKI GEOTHERMAL FIELD (NEW ZEALAND).

#### 2.1 Development history

At Ohaaki, drilling began in 1965, and in the following 6 years 25 deep wells were drilled. From the middle of 1967 until the start of 1972, test discharges were conducted during which time the annual mass withdrawal increased to about 10 Mt/yr (Figure 15). During this "Test discharge period" all the fluid withdrawn was discharged into the Waikato River or the atmosphere; there was no reinjection. 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 in 1990, and has remained at similar values since then (Figure 15). Since commissioning, most of the waste fluid has been reinjected (mainly around the periphery of the production areas) and net mass loss has been about 6 Mt/yr.

Prior to development of the field, the reservoir was liquid-dominated with fluid generally at or near boiling point for depth, similar to Wairakei.

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**FIGURE 15:** Variation of mass withdrawal (solid squares), reinjection (open squares), and deep liquid pressure (solid dots) with time at Ohaaki geothermal field. N = Natural state, T = Test discharge period, R = Recovery period, and P = Production period; taken from Glover et al. (2000)
2.2 Pressure changes

At Ohaaki, deep-liquid pressures decreased by about 15 bar (1.5 MPa) during the test discharge period, but recovered by about 10 bar (1 MPa) in the recovery period before decreasing again after production began (Figure 15). Considering the test periods at each field, the pressure changes at Ohaaki were much greater (15 bar) than at Wairakei (3 bar), despite the mass withdrawal rates at Ohaaki being smaller than at Wairakei (10, 20 Mt/yr, respectively).

2.3 Changes to natural thermal features

Information obtained from Wairakei during the 1960’s and 1970’s led to a better understanding of the relationship between surface features and the geothermal reservoir. It was recognised that the thermal features were fed by fluids escaping from the upper part of the reservoir, along faults or fissures. During the planning stages of the Ohaaki Power Scheme, it was acknowledged that environmental effects might occur, but an Environmental Impact Report was not prepared until 1977, after the test discharge period. In this report the effects of chemical and gas discharges, noise, and thermal pollution on the climate, natural waterways, flora and fauna, were assessed and steps proposed to mitigate the effects. However, the possible effects of exploitation on natural thermal features were not mentioned in the Impact Report, despite the fall in water level in the Ohaaki Pool during the test discharge period and the changes that were known to have occurred at Wairakei.

Prior to exploitation the Ohaaki Field had few natural thermal features (cf. Wairakei); the largest and most significant feature being the Ohaaki Pool, a boiling pool with a surface area of about 850 m². This pool has cultural significance for the local Maori people, and is noted for its beautiful fretted sinter lip and surrounding sinter apron.

Changes in flow rate and water level from Ohaaki Pool

The presence of an extensive sinter apron around the pool indicates that it has overflowed for a long time. Measurements made in a shallow canal from the pool, prior to the test discharge period suggest that normally the flow rate was about 9 l/s. However, it is known that sudden changes in flow rate and water level had occurred in past times. For example, on 25 March 1957 the pool suddenly ceased to overflow, and by 2 April 1957 the water level was about 0.73 m below the overflow channel. On 18 April 1957, the pool was reported to be overflowing again. When visited on 24 April, not only was the discharge flowing down the canal, but water was also spilling over the lip all round and flowing away across the sinter terrace. The total flow rate was estimated to be at least 23 l/s. At this time there was also increased activity (including geysering) in other nearby springs. The increased flow slowly declined, but by 5 June 1957 was still greater than normal. It was considered that the unusual recession was due to mechanical causes; probably the feeding channels becoming blocked by earth movements, and later clearing themselves as pressure increased below the blockage.

Measurements have shown that the overflow rate and water level in the Ohaaki Pool were strongly influenced by the operation of nearby bores (Figure 16). During the test discharge period, when nearby bores were discharged the flow rate decreased until overflow ceased, and then the water level receded. When discharge decreased and was temporarily stopped in 1968, the water level rose, the pool began to overflow, and the flow rate increased to about 8 l/s. Soon after the discharges recommenced, the flow rate stopped increasing for a short period then again decreased rapidly until the pool ceased to overflow. The water level then fell, reaching a level of 1.8 m below the channel on 14 February 1969. About this time it was noticed that some parts of the overhanging edge had collapsed, possibly due to loss of buoyancy support by the water and/or thermally-induced fracturing associated with exposure to the air. No further water level data were collected until 1 October 1971, when the water level was 9.5 m below overflow (Figure 17). During the remainder of 1971 the water level rose reaching a (temporary) maximum of 4.5 m in July 1972, before again declining to 6.4 m in April 1973. There was another gap in the data from then
until May 1974 when the water level was at 5.7 m, after which time the level quickly rose to 3.1 m by November 1974, and then more slowly until the middle of 1976 (Figure 17). There was little discharge from nearby bores during this period and the reason for the temporary drop in level between July 1972 and November 1974 is not known. During the remainder of the recovery period a number of discharge and interference tests were conducted which resulted in perturbations (up to 4 m) to the water level in the pool. The data suggest that, except for these perturbations, the water level generally rose and the pool began intermittently overflowing in October 1981 due to injection of separated water from a nearby bore. From then until August 1988 (start of the production period) the pool overflowed intermittently at rates of up to 2 l/s. During the production period, the water level in the pool has generally been sufficient to result in overflow.

Changes in temperature of Ohaaki Pool
Temperature data are not as detailed as for flow and water level, but show that the temperature of water in the Ohaaki Pool was also influenced by operation of nearby bores. Measurements made prior to well testing (Figure 18) suggest that the water was not always boiling, but surface temperatures were in excess of 85°C. During the initial part of the test discharge period, temperatures decreased to about 65-75°C, but may have recovered in the later part. In the recovery period, temperatures were generally greater than 90°C except when discharges were made from bores in the Western steamfield at which time they decreased to about 75°C.

No measurements were made during the early part of the production period (1989-1992), but the temperature had decreased to about 30-50°C by mid 1992. The temperatures now vary, depending on the amount of bore fluid being injected into the pool.
Changes in chemistry of Ohaaki Pool

The earliest recorded chloride concentration, 1049 mg/kg, was measured in 1929 but no further measurements were made until May 1951. After that date, measurements were made more frequently and show that there were no significant changes in chloride concentration when the pool was in its natural state, during the test discharge period, and early part of the recovery period. The water in the pool was a mixture of a deep parent fluid which had undergone boiling and dilution with a steam-heated (140°C) water. The calcium and magnesium concentrations were 5 and 10 times higher in the pool water than in the deep drillhole waters; this supports the inference that a shallower cooler component had mixed with the deep parent fluid.

Some time between October 1979 and May 1980, the chloride concentration increased by about 150 mg/kg; the increase was probably due to the discharge of bore fluid into the pool. The large variations in chloride, over short periods between May 1980 and May 1987, are likely to have been caused by changes in the amounts of bore water entering the pool.

All samples collected during the test discharge and early part of the recovery periods were taken when the pool had no visible outflow; i.e. no overflow. The fact that evaporation from the surface did not cause increased concentration suggests that subsurface outflow was occurring. Hochstein and Henrys (1988) calculated mass flows for a time when the pool had no visible surface outflow; they obtained an evaporative steam flow of 6.7 kg/s and a subsurface outflow of 30-41 kg/s, i.e. a total mass flow of 37-48 kg/s.

In 1988, a water right was obtained to inject up to 300 t/h (83 kg/s) into the pool to provide overflow. After that time, large-scale discharge of bore water was made into the pool. The average chloride concentration in the pool water increased to 1390 ppm due to the high chloride concentrations in bore water (1620 ppm, at atmospheric pressure). There were also large changes in the chloride concentration during this period as a result of the large variations in inflow, and varied conditions in the permeability of the base of the pool. The low value of 1075 ppm probably indicates no inflow of bore water, and the high of 2175 ppm was probably due to evaporation at a time when leakage and overflow was minimal.

Changes to other thermal features

Before development began, more than 20 thermal features of lesser significance were present at Ohaaki (Figure 19). These included: boiling mud pools (up to 12×6 m), warm pools (up to 80×40 m), and thermal ground.

The surveys showed that in the north-eastern part of the field many of the warm pools and mud pools had dried up and become weakly steaming from vents in the base, and for the remainder there were temperature decreases of up to 38°C. Some patches of thermal ground decreased in area, but others were unaffected (especially in the south-eastern part of the field).
2.4 Ground movements

Pressure drawdown in the reservoir during the test discharge period and since production began has led to compaction within a rock unit above the reservoir, resulting in deformation of the ground surface over a kidney-shaped area in the north-western part of the field (Clotworthy et al., 1995; Allis et al., 1997) (Figure 20). The deformation is associated with draining of fluid from a compressible lacustrine mudstone unit of limited areal extent, but up to 250m thick.
Subsidence monitoring shows that during the test discharge period the centre of the area subsided by 0.15-0.20 m. There was little subsidence during the recovery period, but it restarted at the beginning of the production period and by January 1995 had exceeded 1.2 m (Figure 21). The subsidence has resulted in tilting which has caused water in the Ohaaki Pool (when full) to overflow from the south-western part of the pool in addition to the drainage channel.

Compressional strain has occurred near the Ohaaki Pool at the rate of up to 100 mm/yr, and has been manifested in the form of buckling of the sinter apron south of the pool. Here, the sinter has been upthrust about 20 cm along several \(^\wedge\)-shaped, sub-parallel ridges extending for up to 100 m. These ridges were first noticed in 1994. It is possible that the compressional strain has fractured the base of the Ohaaki Pool, allowing fluid to drain away. Compressional strain has also caused buckling of some steam pipelines, necessitating removal of sections. Tensional strain has occurred around the edges of the subsidence area, resulting in cracks up to 2 cm wide at the ground surface.

Numerical modelling suggests that the subsidence is likely to last for several decades, and that it is non-recoverable, even if reservoir pressures were returned to their pre-development values (Allis et al., 1997).
2.5 Ground temperature change

Shallow (1 m deep) ground temperature measurements made in 1967 (prior to test discharge period), showed that temperatures exceeding 10°C above ambient occurred over most of the north-western part of the field. Additional measurements made in 1983 (recovery period) indicated the approximate area and location of the thermal anomalies was similar to that in 1967. In Dec. 1988, during the commissioning of the power station, a set of 1 m ground temperature monitoring points was established at 25 m intervals along 3 lines across the thermal anomalies (Figure 19). The measurements were repeated in April 1996, and the data corrected for seasonal temperature changes.

Comparison of data from the 1988 and 1996 surveys (Hunt & Bromley, 2000) shows that there were no significant temperature differences on Line 1 through the south-eastern thermal anomaly (Figure 22). On Line 2, there were temperature decreases (10-45°C) over distances of about 200 m; at these places the ground temperatures in 1988 had been 40-70°C above ambient. There was an increase of up to 75°C near BR17; and there ground temperatures are now in excess of 90°C. However, additional measurements suggest these high temperatures are very localised. The area near BR17 lies in a zone of tensional strain associated with ground subsidence and there are numerous cracks in the ground surface. It is probable that the high ground temperatures measured are associated with localised heating of the ground by steam rising through these cracks. Evidence for this is that, on cold mornings during the 1996 survey, steam could be seen rising from the cracks, and grass on the edges of the cracks was observed to be dying. On Line 3, there have been no significant changes, except at three points (Figure 22) where ground temperatures have decreased by 10-20°C (from 44-48 in 1988, to 27-36°C in 1996).

Repeat TIR imagery has also shown the development of numerous narrow, linear thermal anomalies in the north-eastern part of the field, particularly in the vicinity of BR 9. These anomalies are coincident with the tension cracks associated with ground subsidence.

The data indicate that over most of the field, shallow (1 m depth) ground temperatures have not changed since production began in 1988.
2.6 Groundwater level changes

Groundwater levels have been monitored regularly since 1967; at present there are 35 shallow (<50 m deep) and 10 deep (250 m) monitor wells. The data indicate that groundwater levels have generally been unaffected by discharge testing or production. However, in local areas near thermal features groundwater levels have declined by several metres (e.g. BR 3/0, BR 4/0 Figure 23). Data from some very shallow wells indicate the presence of localised pockets of steam- and rainwater-recharged water, which are perched above the principal groundwater aquifer. The water levels in such perched aquifers are more variable.

2.7 Groundwater temperature changes

The temperatures at, or near the water surface, have been measured; in 13 shallow groundwater monitor holes since the test discharge period. Subsequently, more monitor holes have been drilled, and at present measurements are made in 46 monitor holes. Over most of the field the groundwater is cold (ambient temperature 10-25°C), but in two areas which surround known areas of thermal ground the groundwater temperature is warm (25-75°C) or hot (75-100°C).
The monitoring has shown that generally the test discharges had no effect on shallow groundwater temperatures, either hot (e.g. BR3/0, BR6/0; Figure 23) or cold (e.g. BR10/0; Figure 23). One clear exception, however, was in BR4/0: between August 1967 and February 1970, the groundwater was near boiling (90-100°C), but between then and August 1974 the temperature decreased by about 60°C and has remained at 20-25°C since June 1979 (Figure 23). This decrease in water temperature may reflect the onset of a localised cold downflow associated with the pressure drop that occurred during the test discharge period. As the hot water drained downwards it was replaced by cold groundwater which moved in laterally.

There were no significant changes in groundwater temperature during the recovery and production periods. Water in monitor holes that was hot or boiling at the start of the periods has remained hot, or
decreased in temperature by less than 20°C (e.g. BR3/0; Figure 23). Similarly, water in monitor holes that were cold, has remained cold (e.g. BR10/0; Figure 23).

However, there have been exceptions. In BR21/0, at the start of the production period the water temperature was 66°C, but in March and September 1990 the temperature had risen to 97.5 and 101°C respectively (Figure 23). By August 1992, the temperature had returned to 61°C, and all subsequent measurements have shown a steady decline in temperature from that value to about 50°C in late 1994. Except for the two measurements in 1990, the groundwater temperature in this monitor hole has decreased steadily from about 90°C in the early 1970’s to about 50°C in 1995. A similar temperature peak, but of smaller magnitude, also occurred in nearby BR19/0 followed by a decrease of about 30°C in the early 1990’s (Figure 23). Both these monitor holes are in the vicinity of thermal features and the rapid pressure drawdown in the reservoir may have temporarily induced an increased flow of steam to the surface along conduits feeding these features, which in turn may have heated groundwater in the vicinity.

2.8 Seismic activity

Continuous seismic monitoring was carried out for 5 years during the latter part of the recovery and the early stages of the production periods. Seismic activity was low in and around the field prior to commissioning of the power plant and during the first 3 years of production no induced seismicity was detected, even though injection pumping pressures temporarily reached 40 bar (4 MPa) (Sherburn et al., 1993). This behaviour is different from that at Wairakei, where similar pumping pressures in well Wk 301 induced seismic activity. It has been suggested (Sherburn et al., 1990) that the absolute value of wellhead pressure during injection is not the critical factor for inducing seismicity, but instead it is the formation overpressure. At Ohaaki, the injection wells prior to injection were full of fluid and had a slight artesian pressure, so the formation overpressure is almost equal to the wellhead pressure (20-25 bar). At Wairakei, before injection the water level in Wk 301 was at 240 m depth (due to production-induced drawdown) so that during injection the formation overpressure was 44-54 bar (24 bar from filling the well, plus 20-30 bar of pumping pressure).

3. CHANGES AT ROTORUA GEOTHERMAL FIELD (NEW ZEALAND)

Rotorua geothermal field is recognised internationally for the geysers and hot springs at Whakarewarewa thermal area (Figure 24). Geysers are rare natural phenomena world-wide, and Pohutu Geyser at Whakarewarewa is one of New Zealand’s two largest surviving examples. In the early 1950’s, about 220 geysers existed in New Zealand, but by 1990 only about 55 remained; most of the losses being directly attributable to human interference with the geothermal systems.

In the early 1960’s and again in the mid-1970’s, mass flows from Rotorua wells increased sharply as additional wells were drilled (Figure 25), as a result of national electricity shortages (1950 and 1960’s) and oil shortages in the (1970’s). During these times the level of natural hydrothermal activity in Rotorua declined, to reach an all-time recorded low by the mid-1980’s (Cody and Lumb, 1992). During the early 1980’s, public sensitivity to the intrinsic and tourism values of New Zealand’s few remaining geysers increased, as geysers and hot springs in Rotorua progressively failed due to extraction of geothermal fluids. These concerns, together with a realisation that there was no quantified estimate of the volume of fluid extracted in Rotorua, or adequate records of the changes in the surface activity, led to establishment of the Rotorua Geothermal Monitoring Programme in 1982. By 1985, this programme had established that the winter daily mass discharge from all wells was around 31 kt/d, which represented about 40% of the natural deep upflow of the system. In 1986, central government initiated a bore closure programme and a punitive charging regime for remaining well discharges.
3.1 Exploitation and management history

Many Rotorua residents have taken advantage of the underlying geothermal fluids by drilling shallow wells (20-200 m deep) to extract hot water for both domestic and commercial heating. The first geothermal wells in Rotorua were drilled during the 1920’s, by 1944 there were at least 50 wells in use, and by early 1998 over 1150 wells had been drilled. However, many of these were replacement, standby or reinjection wells, so the actual number of producing wells reached a maximum of around 500 in 1985. At that time the total well discharge was estimated to be 25 kt/d (290 kg/s) during summer, rising to 31 kt/d (360 kg/s) during winter (Figure 25).

FIGURE 24: Distribution of geothermal wells in Rotorua City in 1985 (solid dots), monitor wells and thermal areas (outlined by broken lines); circle shows area in which all geothermal wells were closed. Taken from Scott & Cody (2000)
In 1985 only about 5% of well discharge fluids were reinjected back to the production aquifer (typically 20-200 m depths), with most waste waters being discharged into shallow soak holes (<20 m depth). Approximately half the fluid extracted was for residential use and half for commercial use. A bore closure programme in 1987-88 resulted in 106 wells within 1.5 km of Pohutu Geyser (Figure 24) being cemented shut. This, together with the punitive royalty charging regime for all remaining wells, resulted in a further 120 wells outside the 1.5 km radius of Pohutu Geyser being shut. The effect of both forced closures and the royalty charges was a reduction of total well discharge to about 30% of 1985 levels by 1989. Average summer drawoff in 1990 was estimated to be 10.28 kt/d (118 kg/s), increasing in winter by 1.04 kt/d (12 kg/s) to a total of 11.32 kt/d (130 kg/s). The commercial sector then accounted for 68% of the total discharge, and the mass reinjected had risen to 31% of total well discharge.

Net mass withdrawal from the field in 1990 had decreased to near 20% of the amount in 1985. By late 1992 the 141 wells in use were producing 9.5 kt/d, with 5.1 kt/d being reinjected. In 1997, well production was still around 10 kt/d, but of this about 7 kt/d was being reinjected back to source.

### 3.2 Changes in field pressure and water level

A network of 24 monitor (M) wells (typically 80-180 m deep) was established in 1982. During late 1987, all M-wells showed a sudden water level or pressure rise of 1-2m (0.1-0.2 bars, 0.01-0.02 MPa pressure), with ongoing gradual recoveries to date totalling 2-2.5 m. M 16 is typical of wells into ignimbrite aquifers, and M6 is typical of wells into rhyolite aquifers (Figure 26).
3.3 Changes to surface thermal features

Discharges from thermal features at the surface in Rotorua are generally alkaline, high chloride-low sulphate waters, similar to the geothermal waters found in neighbouring shallow wells. No precise early measurements of total natural outflow are available, but estimates are that all hot springs and geysers at Whakarewarewa produced about 34 kt/d prior to any exploitation, and 25 kt/d in 1967. The geysers and most large flowing hot springs have shown responses to the sudden reduction of well drawoff in 1987: at Whakarewarewa, the springs produced about 8.39 kt/d in 1982, which increased to about 9.24 kt/d in 1989-90. The changes in outflows from hot springs show an inverse relationship to bore discharge, and are consistent with more geothermal fluid now being available for natural spring outflows as a consequence of reduced well drawoffs.

Springs and geysers
At present, geyser activity in Rotorua is confined to Whakarewarewa, where at least 65 extinct geyser vents are recognised. On Geyser Flat there are seven intimately connected and interactive geysers, such that data from any single one are not indicative of overall trends of Geyser Flat activity. Natural changes are also occurring which compound the problems of interpreting geyser changes through time.

At Geyser Flat, qualitative historical data from the 1890’s, and later instrumental and visual records from the 1950’s, present a clear picture of declines in outflows and failing geyser activity during 1950’s-1980’s, but with a pronounced recovery since 1987 to present day (Figure 27).

Pohutu Geyser: Full column eruptions of Pohutu (largest geyser on Geyser Flat) typically reach up to 21 m height, and occur 10-60 times each day, historically averaging 30-60% of any day in eruption (Figure 27). During the 1960’s-1980’s, Pohutu showed a pronounced shift to more frequent but shorter duration eruptions, possibly because of reduced aquifer pressures, but its total daily eruption times showed no significant change. In late 1986, it underwent a period of several months with no strong full column eruptions but many long episodes of dry steam emission, a phenomenon unseen before or since then. Eruptions of Pohutu have not shown any changes conclusively related to the well closures of 1986-87, except for the disappearance of dry steaming emissions. At present, it continues to have numerous short eruptions (2-5 minutes), but recordings from December 1997 to February 1998 show a shift to longer duration eruptions, with about 20% now lasting 30-50 minutes (Figure 27).

Te Horu Geyser: Until about 1972, this geyser used to erupt 2-7 m high with about 100 l/s outflows which occurred as frequently as 10-15 times each day, but after that time eruptions and boiling ceased. In January 1998, water began rising in the vent, then in December 1998, minor overflows occurred, followed in March-April 1999 by stronger overflows.

Wairoa Geyser: This last erupted naturally in December 1940 after which its water level fell to >4.5 m below overflow and the water became acidic. However, in early 1996, its water level rose to 3.2 m below overflow, with continuous powerful boiling and it remains so to date.

Kereru Geyser: Eruptions 10-15 m high, several times a week, occurred up until about 1972; after which time no large natural eruptions are known until they resumed in January 1988. Since then, moderate-large eruptions have occurred every few days or weeks, and occasionally up to seven per day have been observed in daylight hours. It remains active to date, with an exceptionally long eruption (about 5 minutes) occurring on 12 November 1997.

Papakura Geyser: This geyser stopped erupting in March 1979, after a 90 yr period during which it was known to have faltered very briefly only three times. The cessation of eruptions from Papakura was directly responsible for initiating the Rotorua Monitoring Programme in 1981. Papakura has not recovered to date, although in October 1997 the fluid in the vent had heated to about 60°C and become clear and alkaline once more, although still without any boiling or eruptions since 1979.
Examples of environmental changes

Waikite Geyser: This last erupted in March 1967, since then the vent has remained dry and weakly steaming. In June 1996, its previously 8.5 m deep and dry vent suddenly filled with boiling water which rose to within 2.3 m of overflow. In June 1997, its water levels retreated suddenly to >8m depth, but returned in late 1998 to about 3m below overflow. An analysis of waters collected in 1996 showed very low chloride and high sulphate concentrations, confirming an absence of deep geothermal waters.

Okianga Geyser: During the late 1970’s and early 1980’s no eruptions were observed, but since about 1992 it has been reliably erupting every 25-35 minutes to about 7 m high.

Parekohoru Spring: In 1985-86, this spring ceased overflowing for several days each winter; the first such stoppages known in historical times. Since 1988 there have been no further cessation of flows. Boiling surges with large overflows recommenced in 1995, similar to reports of earlier this century, and continues to date.
Rachel Spring: This is the sole remaining boiling and flowing alkaline spring in the Government Gardens. Prior to 1987, the last recorded overflowing and boiling episode was in 1967. From then until 1987 its water level had remained at 1.2-1.7 m below overflow, and the temperature at 70-80°C. However, since late 1988 it has been continually boiling and flowing at 7-12 l/s. It still has brief cessation of overflow, but these stoppages last only a few days and since 1988 its water level has never fallen more than 0.1 m below overflow.

Kuirau Lake: From late 1940’s -1987, the water was warm (about 45–50°C), acidic, low chloride and there was little or no overflow. However, from 1988 until November 1997, Kuirau Lake consistently overflowed at 40-60 l/s and 70-80°C, with high chloride and low sulphate alkaline waters. The rise and heating of Kuirau Lake since 1988 has killed all of the vegetation surrounding its shores; including trees up to 5m high and 20-30 years old, which had grown since the lake cooled in the late 1940’s. Since December 1997, outflow has fluctuated between about 25 and 50 l/s

Tarewa Springs: Over the last 14 years, water levels have typically been about 1.5 m below overflow. In March 1998, several of the larger Tarewa springs, within Kuirau Park, commenced boiling once more and in some cases their water levels rose to overflow. In July 1998, geysering activity occurred in three of the springs. Two features had been infilled or built over while inactive, and their reactivation has created considerable problems.

Hydrothermal eruptions
Since records began in 1845, at least 91 explosive hydrothermal eruptions have occurred. The frequency and distribution of these appear to show a correlation with larger scale disturbances of the field imposed by both human and natural activity. The 1886 volcanic eruption of Mount Tarawera (about 20 km east of Rotorua) caused pronounced changes to thermal activity throughout Rotorua, with many previously extinct or passively flowing springs suddenly boiling, erupting and overflowing. New geysers erupted at Whakarewarewa, and many hydrothermal eruptions and resumed hot spring overflows also occurred in the weeks and months following the volcanic eruption.

An area of high steam flow occurs at the southern end of Lake Rotorua, and spectacular large hydrothermal eruptions were common there in the 1890’s-1900’s. At that time the lake level was uncontrolled, but since the lake level has been controlled the eruptions have become less frequent.

In the early 1890’s a railway line was built into Rotorua. The construction works resulted in extensive drainage of previously swampy, peaty ground. Writers at that time attributed several hydrothermal eruptions there to the effects of the recent drainage works.

There was also an increase in the number of hydrothermal eruptions during the 1950’s-1960’s when there was increased well drilling and hot water drawoff.

4. CHANGES IN TONGONAN GEOTHERMAL FIELD (PHILIPPINES)

The Bao-Banati thermal area is located in the southwest part of the Greater Tongonan Geothermal Field (GTGF), approximately 2 km from the Malitbog reinjection sink, and 4 km from the Mahiao-Sambaloran reinjection sink and Tongonan I power plant. The thermal area contains the largest and most impressive thermal manifestations within the field and includes numerous hot springs, fumaroles and steaming vents which discharge neutral-pH chloride waters. The hot springs are distributed along the Bao River and the Banati Creek, and fumaroles and steaming vents occur near the confluence of the Bao and Malitbog rivers.

The chemistry of the Tongonan thermal springs was first determined in 1965. Surveys were also conducted in 1973 and 1979 prior to exploitation. After six years of drilling and discharge testing an assessment of the response of the thermal springs was made, but no significant changes in discharge
Examples of environmental changes Lecture 2

chemistry of the springs was found. In 1983, a monitoring programme to measure any effects of exploitation on the thermal features in the GTGF was started.

In the early 1970’s, thermal activity in the area included geysering and steaming features. The most prominent features were hot springs no. 1, 4, and 36. Hot spring no. 1 is popularly known as “Orasan”, which means clock in the local vernacular, due to its periodic geysering activity. Hot spring no. 4 has one of the greatest mass flowrates (20 kg/s), and hot spring no. 36 has the highest chloride concentration (3600 mg/kg).

Prior to development, the springs discharged neutral-pH chloride waters with 2500-4000 mg/kg of Cl, 150-180 mg/kg HCO₃, and 40-80 mg/kg SO₄. The major cations include Na (650-1400 mg/kg), K (42-107 mg/kg) and low Ca (12-48 mg/kg). Trace amounts of Mg and Fe are also present in less than 1.0 mg/kg. Assuming maximum steam loss at 100°C, the quartz geothermometer predicts temperatures of 160-180°C for the reservoir feeding the springs. The chemistry suggests the Bao-Banati springs mark the outflow sector of the field.

4.1 Flowrate changes

After commissioning of the Tongonan 1 power plant in 1983, a significant decline in the activity of the Bao-Banati thermal springs was observed. Most notable was the cessation of geysering activity, with a corresponding decline in mass flowrate from hot spring no. 1. Hot springs no. 4 and 36 showed a decline in mass flowrate, and eventually ceased discharging in 1985. Other hot springs in the area exhibited a similar declining trend in mass flowrate. The total flow was approximately 85 kg/s in 1983, which reduced to 55 kg/s in 1984, and to 10 kg/s in 1992. Most of the springs dried up or became reduced to non-flowing pools. For example, hot spring no. 16 declined in mass flowrate from 8.8 kg/s in 1982 to 1 kg/s in 1987, and ceased discharging in 1989 (Figure 28).

In December 1982-January 1983, a noticeable increase in mass discharge of the springs was observed coincident with 65 kg/s reinjection into well situated about 2 km from the springs. A similar change occurred again in May-August 1996, coinciding with the further use of reinjection well 5R1D at a higher reinjection rate of 224 kg/s. At both times there was an increase in the measured mass flowrate of hot springs no. 1, 7, and 8. Hot spring no. 3, on the northwest bank of the Bao River displayed more frequent and vigorous geysering during the height of this reinjection. Hot springs no. 4 and 36, which had dried up in 1985, re-appeared during the height of reinjection but both features disappeared again after the reinjection stopped.

![FIGURE 28: Changes in mass flowrate of hot spring no. 16 with time, Tongonan, Philippines; taken from Bolanos & Parilla (2000)](image-url)
4.2 Chemistry changes

In 1981-1982, the chloride concentration of the Bao-Banati springs was 2500-3500 mg/kg, similar to that of nearby exploration wells. After exploitation began in 1983 the chloride concentration of the springs steadily declined to a low of 500-1500 mg/kg in 1989 (Figure 29). The decline in chloride was due to the decrease in reservoir pressures, associated with mass extraction from the reservoir (Figure 30) which caused a reduction in the contribution of fluid from the deep geothermal reservoir.

During 1990-1995, a temporary increase in chloride concentration of the springs was observed. This can be attributed to the increase in brine reinjection at Tongonan I as a consequence of declining well enthalpies and increasing generation during the period. The increase in reinjection temporarily increased reservoir pressures, and effectively increased the contribution of deep geothermal fluids to the spring discharges. However, in 1995 chloride concentrations in spring waters appear to have declined as reinjection in Tongonan decreased. This suggests the absence of reinjection fluid breakthrough coming from the Mahiao-Sambuloran reinjection sink, which had chloride concentrations of 12500-16000 mg/kg.

During the pre-commissioning activities in the Malitbog Sector in May-August 1996, an increase in
Examples of environmental changes

FIGURE 31: Relation between rate of reinjection into well 5R1D, and changes in massflow rate and chloride of hot spring no. 1; taken from Bolanos & Parilla (2000)

chloride concentration was observed in the hot springs. At this time, about 140-220 kg/s of brine was being reinjected into reinjection well 5R1D (Figure 31). With conclusion of the Malitbog plant pre-commissioning activities on 14 August 1996, reinjection into 5R1D was stopped. Chloride concentrations then declined from a peak of 1900 mg/kg in mid-August 1996 to 1300 mg/kg in November 1996 (Figure 30), which indicated breakthrough of reinjected fluids from 5R1D to the Bao-Banati springs had previously occurred. This was later confirmed by tracer testing. Full operation of the Malitbog Plant commenced in April 1997 and 5R1D was put back on line at a reduced reinjection rate of 66-119 kg/s. An increase in mass flow and chloride of the springs was again observed (Figure 31).

In late 1997 and early 1998, hot spring no. 1 showed an increase in chloride (2200 mg/kg) which surpassed previous levels (1900 mg/kg) in 1996-1997. However, flow from this spring declined from 3.88 kg/s in August 1997 to 0.02 kg/s in March 1998. The increase in chloride, but decline in mass flowrate, cannot be associated with the breakthrough of reinjection fluid from well 5R1D, as was the case in May-August 1996. Probable causes are: a long drought which effectively reduced the contribution of near surface groundwaters to the spring discharges; and a shift in the direction of flow of reinjection fluid towards the Malitbog production sector in the northeast, rather than towards the natural outflow in the southwest. This shift is shown by the increasing chloride concentration in production wells near the Malitbog reinjection sink (5R1D, 5R4 and 5RB wells). In well 515D (northeast of well 508D), chloride increased from 7500 mg/kg in June 1997 to 9500 mg/kg in March 1998.

4.3 Changes in quartz geothermometer temperatures

There was a decline in quartz geothermometer temperatures, which is consistent with decreased contributions from deep geothermal fluids and increased dilution by shallow ground waters (Figure 32). However, the quartz geothermometer temperatures temporarily recovered in 1996 during the pre-commissioning activity in Malitbog, after which they resumed the decline, only to increase again in April 1997 during commissioning of Malitbog. The increases in quartz geothermometer temperatures during these periods provide additional evidence of the breakthrough of reinjected fluid from 5R1D to the hot springs.
Monitoring of the Bao-Banati thermal springs during operation of Tongonan 1 Power Plant shows there have been:

a) Significant declines in the flow rates from the springs;
b) A demise or reduction in the character of some springs to non-flowing pools;
c) A decline in the chloride concentration of the waters;
d) Declines in quartz geothermometer temperatures.

The changes are similar to those observed in thermal springs at Wairakei and Ohaaki geothermal fields in New Zealand, and are attributed to the decrease in reservoir pressures which have caused a reduction in the contribution of deep geothermal fluids to the waters emerging from the springs.

During reinjection of waste brine into well 5R1D (Malitbog sector) as part of pre-commissioning trials and after commissioning of the Malitbog Plant, there were increases in flowrate, thermal activity, and mineralization of the springs. These changes are interpreted as being caused by breakthrough of reinjected fluid from this well to the springs.

5. CHANGES AT PAMUKKALE (TURKEY)

One of the most spectacular natural geothermal features in the world is the travertine terraces at Pamukkale, in south-western Turkey. In 1993, a joint project was started involving Hacettepe University (Ankara) and the Ministry of Culture of Turkey, aimed at conserving the terraces. This on-going project is also supported by UNESCO, which has declared the area a World Heritage Site. The need for this project arose after intensive tourist activity had caused environmental pollution in the area.

The pure white travertines have become darker, yellowish and brownish after establishment of tourist sites and hotels in the area above the terraces, and this is especially noticeable at the end of the summer tourist seasons. These hotels take the hot water directly from the spring outlets or by open channels to swimming pools, after which it is released onto the travertine. This procedure has several adverse effects.

• Outgassing of CO₂ from water in the pools decreases its travertine depositing capacity;
• Swimmers in the pools leave organic relicts which cause a rapid growth of algae, which cause a change in colour of the travertines.

The lack of a sewage system is another major source of pollution. Each hotel has a septic tank dug into the travertine and, although lined with cement, they leak waste water which emerges at the bottom of the
terraces. There are large amounts of algae in these places because the leaked water is rich in nutrients. To prevent this pollution, protection areas have been delineated, based on geological and hydrological information.

A further problem is mechanical damage to the surface of the terraces caused by people or animals walking on the travertines; this deforms the calcite crystals and deters their formation. To prevent this occurring, a program has been developed to enhance travertine deposition and for their protection against pollution. This includes (Simsek et al., 2000):

- Construction of about 4.7 km of new concrete channels from the four main springs to the travertines, to prevent loss of thermal water by leakage along the water path. These channels are covered with concrete lids to reduce outgassing before the water reaches the travertine area. The lids also serve to stop sunlight reaching the water, thus deterring growth of algae in the channels;
- Building intake structures at the springs for better management of the hot waters;
- Construction of fences around the springs and water outlets to the travertine terraces;
- Prohibiting walking on the white travertine area;
- The old asphalt road crossing the travertines has been closed, and replaced by new terraces constructed to imitate the natural morphology of the area;
- Removal of septic tanks and their replacement by portable toilets;
- Moving the hotels and other tourist facilities from above to below the travertine terraces.

APPENDIX I

Vertical distribution of water in the borefield area several years after the start of production at Wairakei geothermal field, New Zealand; taken from Allis & Hunt (1986).