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# Rotorua Geothermal Field Management Monitoring

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Cover Photo: Pohutu Geyser – Whakarewarewa Thermal Valley, Rotorua.

# Executive Summary

The Rotorua field is unique in that it contains one of New Zealand's last remaining areas of major geyser activity located at the Whakarewarewa thermal valley (Allis and Lumb, 1992) and is therefore of great regional, national and international significance. On a local scale the field has social, cultural, intrinsic, and economic values (Environment B·O·P, 1999).

The objective of this report is to provide a summary of monitoring and technical information on the current status of the Rotorua geothermal field. It is an update of the Rotorua Geothermal Field – Response to Field Closure 1987-1992 report (Grant-Taylor and O'Shaughnessy, 1992) and an update to the Surface Activity Monitoring Overview Report – 1998 (Hodges, 1998). Since those reports were prepared, Environment B·O·P's Geothermal Regional Plan (the Plan) for the field became operative in July 1999. The Plan sets out policy, rules to achieve this, and requires Environment B·O·P to undertake monitoring and research necessary to support policy initiatives in the Plan.

Conceptual models have been developed for the Rotorua field which summarises data, and identify the important processes that control the flow of fluid, energy and chemicals within the field. Computational models were then developed to describe the effects of fluid withdrawal from the field on the natural outflow at Whakarewarewa. Modelling confirmed that the closure of bores within the 1.5 km zone was important for recovery at Whakarewarewa, and that the impact of withdrawal on flow at Whakarewarewa is proportional to the distance from Whakarewarewa (Burnell and Young 1994) (Burnell, 1998).

The computational models also suggest that as a result of the closure programme the flow from the reservoir into Whakarewarewa would increase from 190 kg/sec to 275 kg/sec (the actual data shows an increase from 200 kg/sec to 300 kg/sec), and an outflow at Kuirau Park/Ohinemutu increasing from 0 kg/sec to 15 kg/sec of 180ºC fluid (the measured value in 1993 was about 40 kg/sec, including a large ground water dilution component) (Burnell and Young 1994).

The 1992 to 2000 period has been the greatest recovery of surface features activity, across the field. There has also been unprecedented eruption activity from Pohutu geyser and resumption of flow at a number of springs at Whakarewarewa together with reactivation of springs in other areas of the field that had previously been dormant. The response of features such as geysers and hot pools is difficult to assess on an individual basis because natural and human induced changes can mask overall trends. However, a heat flow survey of natural features is a way of identifying changes in output. A survey at Whakarewarewa was completed in late 2000 in a similar way to two previous surveys. Overall the total output for the surface features at Whakarewarewa has increased by 30% over the 1984 value, and is now within 10% of the value for 1967, which is the most reliable estimate for discharge when the field is only lightly stressed.

There has been a slow rising trend in the water levels in monitoring bores across the field. This increase is about 1m and cannot be accounted for due to rainfall variation, closure or changes in usage. A possible explanation for the slow rise in water levels is an increase in the total output from the field. It has been shown by Kissling (2000) that it is possible for heat and mass output to vary by several percent on timescales of decades. This rise may have started early in the monitoring programme in the 1980's and would have been obscured by the downward trend in water levels in the field until 1986 bore closure.

The general state of knowledge of the field is good although there are a few areas where the natural variability of geothermal features obscures detailed assessments of behaviour. Despite these difficulties (which are particularly pronounced in trying to quantify natural features) it is clear that the field has made a very significant response to the changes which were made in the late 1980's.

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# Chapter 1: Introduction

## 1.1 Introduction

The objective of this report is to provide a summary of monitoring and technical information on the current status of the Rotorua geothermal field. It is an update of the Rotorua Geothermal Field – Response to Field Closure 1987-1992 report (Grant-Taylor and O'Shaughnessy, 1992) and an update to Surface Activity Monitoring Overview Report – 1998 (Hodges, 1998). Since those reports were prepared, Environment B·O·P's Regional Resource Management Plan for the Rotorua Geothermal Field became operative in July 1999.

The key objective of the Rotorua Geothermal Regional Plan (the Plan) is to protect and bring about recovery and the ongoing protection of geothermal surface features while providing allocation for various uses. The Plan sets out policy and rules to achieve this and requires Environment B·O·P to undertake monitoring and research necessary to support policy initiatives in the Plan. This report presents results of the monitoring information and technical investigations undertaken by Environment B·O·P and its consultants and will cover the following subject areas:

- Historical background and management framework;
- Physical aspects of the field, geology, hydrology;
- Field monitoring programme and results;
- Field modelling and results;
- Usage changes;
- Natural thermal activity.

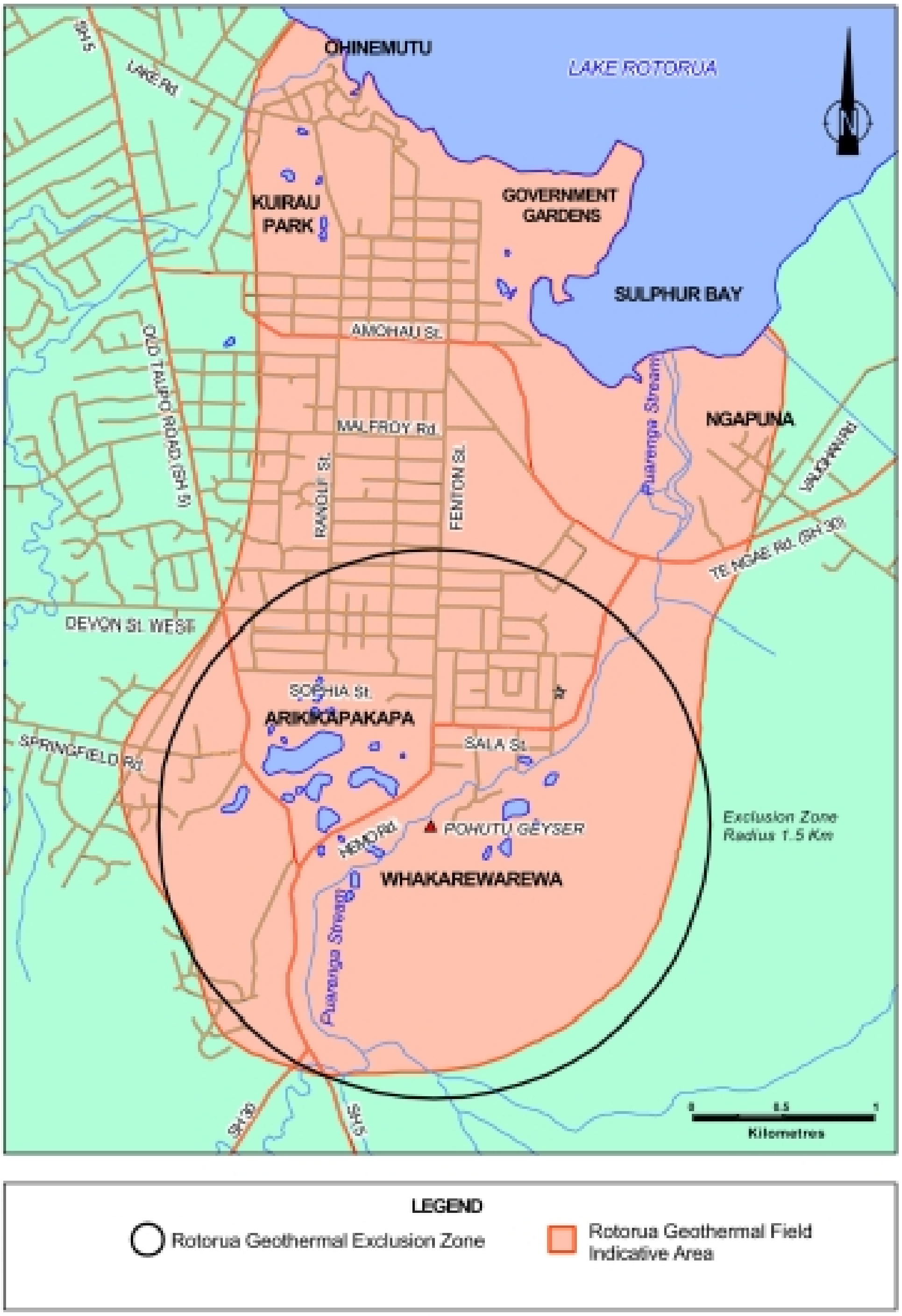
# Chapter 2: Background and Field Management

The Rotorua geothermal field is located in Rotorua City and underlies much of the city and the southern margin of Lake Rotorua. The field has an area of between 18-28 km$^2$ as defined by electrical resistivity surveys. Natural thermal activity is generally confined to three areas of the geothermal field: Whakarewarewa/Arikikapakapa in the south, Kuirau Park/Ohinemutu (on the shore of Lake Rotorua) to the north and Government Gardens/Ngapuna/Sulphur Bay to the northeast which is also on the shore of Lake Rotorua (Figure 2.1).

The Rotorua field is unique in that it contains one of New Zealand's last remaining areas of major geyser activity located at the Whakarewarewa thermal valley (Allis and Lumb, 1992) and is therefore of great regional, national and international significance. On a local scale the field has social, cultural, intrinsic, and economic values (Environment B·O·P, 1999).

Changes to the characteristics of the Rotorua Geothermal Field are defined by time periods where major use was made of surface activity followed by field exploitation from drilling and abstraction of geothermal fluid from bores and the various field management regimes. These time periods are generally defined as:

- Pre-bore exploitation - 1800 to 1950;
- Exploitation of the field from bores - 1950 to 1986;
- Bore closure and post closure field recovery phase - 1986 to 1992 ;
- Field Management Plan and surface features recovery - 1992 to 2001.



**DISCLAIMER**

This map shows an interpretation of the geothermal features of the Rotorua area. The small scale of this map has necessitated the omission of some small features and the exaggeration of others in the interests of clarity. The map should not be used for any work where site specific investigations should be made.

*Figure 2.1 Extent of the Rotorua geothermal field as defined by the electrical resistivity surveys.*

## 2.1 Pre-exploitation – 1845 to 1950

Pre exploitation is generally known as the time when there were few bores drilled into the field but extensive use was made of hot water springs across the field for bathing, cooking and other traditional uses. Geysers, flowing springs and other active thermal features also attracted visitors to the Rotorua area. Considerable human modification to hot water springs and manipulation of flows occurred to provide for bathing and spa development. Reported historic accounts generally noted substantial surface activity from thermal areas of the field and the evidence of this was the increasing number of tourists that visited the area. It was also noted from early scientific accounts that geysers and other thermal features showed an enigmatic behaviour, which is a phenomenon that is now a widely accepted characteristic of geothermal systems.

## 2.2 Exploitation Phase – 1950 to1986

During the 1950's and 1960's geothermal energy was considered a cheap and convenient energy source and this resulted in an increase in the number of bores drilled into the field to abstract geothermal fluid. Population growth and energy crises in the 1950's and 1970's significantly contributed to further increases in bores drilled. (Ministry of Energy, 1985). This was also the time when development of Rotorua City proceeded rapidly and this is likely to have influenced the field and surface thermal activity due to site levelling, draining, road making and building development (Ministry of Energy 1985).

In 1953 central government passed the Geothermal Energy Act, which required bore owners to obtain licences for deep bores (<61 m) unless the bore was for domestic purposes. The government then delegated the issuing of bore licences to the Rotorua City Council under the Rotorua City Empowering Act 1967. This legislation focussed on the utility use of the geothermal field, with little concern for the benefits or detriments that extensive use of geothermal fluid may have on the field and surface thermal feature activity.

No licences were ever issued during the 19 years the Rotorua City Empowering Act 1967 was in force and administered by the Rotorua City Council. Many bores were drilled and fluid abstracted and as a consequence of this development of the field progressed in an unplanned way with no regard for the sustainability of the resource or protection of surface features.

In the late 1970's there was a significant decline in thermal activity at Whakarewarewa and other thermal areas across the field. For instance in 1979, two thermal features failed. Papakura geyser ceased, spring flow from Korotiotio stopped and weaker eruptions became more prevalent from Pohutu geyser through the 1980's (Grant-Taylor and O'Shaughnessy, 1992). This decline was considered to result from a reduction in the geothermal aquifer water level due to the extensive withdrawal of geothermal fluid from bores across the field.

Public concern was expressed about the possible damaging effects that bore draw off was having on thermal activity at Whakarewarewa. In 1980, the Minister of Energy and Rotorua District Council announced guidelines for dealing with drilling and use of geothermal energy in Rotorua. Amongst these, was a ban on drilling anything other than replacement bores within a 1.5 km radius of Pohutu Geyser (Figure 2.1). Also in 1980, the government agreed to set up the Rotorua Geothermal Monitoring Programme for the field as it was recognised that there was strong need to quantify the volume of fluid abstracted from the field, record changes in the geothermal aquifer and note changes in surface activity.

The monitoring programme began in 1982, and included establishing a network of monitoring bores to record water level, temperature in the geothermal aquifer and also geochemical investigations. Initial findings from the monitoring programme indicated that a large fraction of geothermal fluid from the field was wasted through inefficient use and used fluid being disposed of to shallow ground (up to 20m in depth) soakage.

From 1982 to 1986 the monitoring of the geothermal aquifer water levels indicated the field was not stable as the average geothermal aquifer water level was declining from year to year and consequently the natural surface out flow from thermal areas was also declining. The drawoff from bores was clearly having an effect in reducing water levels and surface flows. As a result, the Rotorua Geothermal Taskforce was formed in 1983 to establish the extent of geothermal fluid drawoff from the field and to investigate methods of reducing that drawoff (Ministry of Energy 1985).

## 2.3 Bore Closure and Post Closure Field Recovery - 1986 to 1992

Strengthening concern over the effect of geothermal fluid withdrawal on the geysers at Whakarewarewa and the apparent lack of action from local authorities led the government to take emergency measures in 1986. This included revoking the 1967 Rotorua Empowering Act, ordering the closure of all bores (106) within a 1.5 km radius of Pohutu Geyser and closure of all government department bores in Rotorua City.

The Government also introduced a royalty scheme for those abstracting geothermal fluid across the field. This brought about a reduction in bore numbers from 376 to 141, and a reduction in users from 1800 to 500, which resulted in about 30% reduction in total mass withdrawal (Grant-Taylor and O'Shaughnessy, 1992). Deep bore reinjection of geothermal fluid back into the field increased from 5% to 54 % by about 1992, resulting in a reduction of net withdrawal from 27,500 to just 3,800 tonnes/day or 86% reduction (O'Shaughnessy, 2000).

During late 1987 most monitoring bores showed an increase in water level or pressure of between 1-2 m (0.1-0.2 bars or 0.01-0.02 MPa pressure) and by the end of 1988 pressure gains were essentially complete. By about 1992 water levels in the field fluctuated seasonally around an apparent uniform level. The recovery in water level resulted in an increase in geothermal outflow at thermal areas across the field. At Whakarewarewa the outflow increase was estimated to be between 950 and 2,750 tonnes/day and at Kuirau Park the outflow increased to approximately 5,000 tonnes/day (Grant-Taylor and O'Shaughnessy, 1992).

By 1992 many geothermal features at Whakarewarewa had increased in activity and the resumption of flow from springs. For example, Pohutu geyser produced higher energy eruptions and outflows from Parekohoru Spring increased (Cody and Lumb 1992). Likewise thermal areas in other parts of the field showed a resumption or increase in activity, for example, Rachel Spring (Government Gardens) resumed boiling and strong over flow after many decades of little or no overflow or boiling.

The general pattern was one of recovery of geysers, springs and other thermal features across the field. This recovery clearly demonstrated that preservation of pressure or mass within the aquifer is important in the maintenance of surface features. This confirmed that the 1986 decision by the Government to close bores within the 1.5 km zone and imposing a resource royalty regime was the right one.

## 2.4 Field Equilibrium and Surface Features Recovery - 1992 to 2001

The 1992 to 2001 period has been the greatest for recovery of surface features activity, yet there has been only a slow rising trend in the water levels in monitoring bores across the field. This increase is about 1m and cannot be accounted for due to rainfall variation rises due to closure or changes in usage.

There has also been unprecedented eruption activity from Pohutu geyser and resumption of flow at a number of springs at Whakarewarewa, together with reactivation of springs in other areas of the field that had previously been dormant. For example in 1998 the Tarewa springs in Kuirau Park thermal area reactivated resulting in damage to property. A hot spring began flowing under the garage floor of home units at Tarewa Road and associated geyser activity from adjacent springs resulted in the demolition and removal of the dwelling concerned. Investigation showed that the dwelling had knowingly been built on a geothermal feature and that at the time of construction pipes were laid to allow drainage of the feature if it reactivated (Cody, 1998). This highlights the issue of previous town planning decisions having localised effects on surface features resulting in an increased risk of damage to property as the field recovers. Environment B·O·P and Rotorua District Council have since jointly undertaken an inventory of geothermal features to assist in better identifying the hazard risk and to aid in the protection of surface features.

## 2.5 Management Framework for the Rotorua Geothermal Field

The Rotorua Geothermal Regional Plan was proposed on 21 January 1996. After resolution of references by the Environment Court the Plan was made operative in July 1999. The aim of the Operative Rotorua Geothermal Regional Plan are to ensure that the Rotorua geothermal resource retained its value and potentials, while: protecting geothermal surface features, protecting tikanga Maori, identifying and where practicable enhancing available geothermal resources, providing for the allocation of that resource for present and future efficient use and, managing and controlling adverse effects on the field (Environment B·O·P, 1999). Some of the key polices of the plan are;

- Retention of the 1.5 km radius mass abstraction exclusion zone around Pohutu Geyser to protect the outstanding geothermal features at Whakarewarewa;
- No net increase in fluid abstraction in from the field. This has been set at the mass extraction level for 1992 as the maximum permitted for the field (4400 tonnes per day for the field);

- Reinjection of all abstracted fluid - additional tonnes of fluid have been able to be allocated through reinjection, while still allowing a recovery in water level;
- Setting of strategic water levels in the geothermal aquifer to sustain geothermal surface features and protect these resources into the future;
- Protection of surface features from physical destruction, restoration of outflows and the avoidance or mitigation of natural geothermal hazards.

## 2.6 Monitoring Programme

To effectively manage the geothermal field requires information about the geothermal resource. To achieve this monitoring and information gathering requirements were included in the Plan. A variety of different tools to monitor and predict changes in the field are available to Environment B·O·P, these include: a field model, the assessment of water level monitoring trends, information from bore construction and testing, and the monitoring of chemical and thermal changes across the field.

### 2.6.1 Field Monitoring

Environment B·O·P has in place a monitoring programme to gather information about the geothermal field and geothermal aquifer. Environment B·O·P inherited an array of monitoring bores that were drilled as part of the government monitoring programme. Environment B·O·P has continued to maintain and collect monitoring data from these bores and this monitoring has proved to be the best indicator of the state of the field at any one point in time. Graphing water level data gives a comparative picture of trends and an indirect picture of what is happening in the geothermal aquifer. Strategic equilibrium water levels have been set in the Plan as a method of sustaining the geothermal features into the future. Water level monitoring in three bores is used to give effect to this policy and water level monitoring also provides valuable data for computational modelling.

A programme of monitoring natural features has also been implemented by Environment B·O·P to detect changes in activity at three main thermal areas of the field and in particular the highly significant geysers, springs and pools at Whakarewarewa Thermal Valley. Thermal features at Whakarewarewa and other thermal areas of the field have been shown to be highly sensitive to changes in the water level (pressure) in the aquifer (Grant-Taylor and O'Shaughnessy, 1992).

Monitoring the activity of key thermal features across the field provides an indicator of the geothermal outflow from the field. However it must be recognized that the geysers and springs of the field express a large amount of variability in activity due to natural and human induced changes. This is because geysers and springs are influenced by metrological conditions such as rainfall and barometric pressure and changes to the natural conduits that provide outflow pathways to the surface. Therefore interpretations about the state of the field aquifer made from surface feature monitoring information needs to be carefully considered.

### 2.6.2 Field Modelling

Modelling is a useful tool that brings together theoretical understanding about the field and then tests these against monitoring data and changes in abstraction and reinjection to predict field changes. Earlier models successfully predicted the increase in water level in the geothermal aquifer and changes in outflow from thermal areas as result of the 1986 bore closure. Environment B·O·P commissioned Industrial Research Limited to develop a computational model for the Rotorua Geothermal Field in 1993. This model is based on earlier conceptual and computer models that were developed during the government monitoring programme and revised models commissioned by Environment B·O·P.

The current model was used to test sets of scenarios associated with setting the policy in the plan with regard to abstraction and reinjection of thermal fluid. This model also confirmed that closure within the 1.5 km zone was important for recovery at Whakarewarewa and that the effects of withdrawal on the outflow from Whakarewarewa is proportional to the distance of abstraction from Whakarewarewa.

# Chapter 3: Physical Aspects of the Field

The Rotorua Geothermal Field is one of many geothermal systems found in the active band of Quaternary volcanism spanning from Mt Ruapehu in the south, through to White Island in the north that is known as the Taupo Volcanic Zone (Figure 3.1). The Rotorua geothermal field is located within the Rotorua rhyolitic volcanic centre at the southern margin of Lake Rotorua. The field area covers approximately 18-28 km$^2$ as defined by electrical resistivity surveys (Figure 2.1).

Data and structural descriptions of the field are largely based on the intensive monitoring carried out between 1982 and 1985, and published in the Technical Report of the Geothermal Monitoring Programme (Mahon, 1985) which drew together previously published information and new data.

The most significant source of information used to assess subsurface geology and structure of the field is that gained from interpretations of geological drill hole logs. The most accurate geological information covers only the upper layers to about 300m depth because most of this data is obtained from bores designed to deliver hot water rather than geological information. Detailed measurements of the water chemistry in the deeper geothermal bores, in ground water, and from natural features allowed interpretations of: water source, movement and mixing which provides information on the control mechanisms for the local hydrology of the field.

## 3.1 Geological Features

The Rotorua geothermal field occupies the southern portion of the Rotorua basin, which is now partly occupied by Lake Rotorua. This basin was formed from the caldera generated by ground collapse following the eruption of the Mamaku Ignimbrite, centred on the present day Ngongataha. This ignimbrite eruption has been dated using fission track dating methods at about 140,000 years B.P (Murphy and Seward, 1981), and at 220,000 years B.P by isotope dating methods (Wilson et al, 1995).

Wood (1992) describes infilling of the caldera basin with rhyolite domes, including domes buried beneath the northwest portion of the city, rhyolite lava flows and lake deposits. Lake deposits are found as much as 90m above the present lake level as a result of earlier damming at the northern outlet of Lake Rotorua.

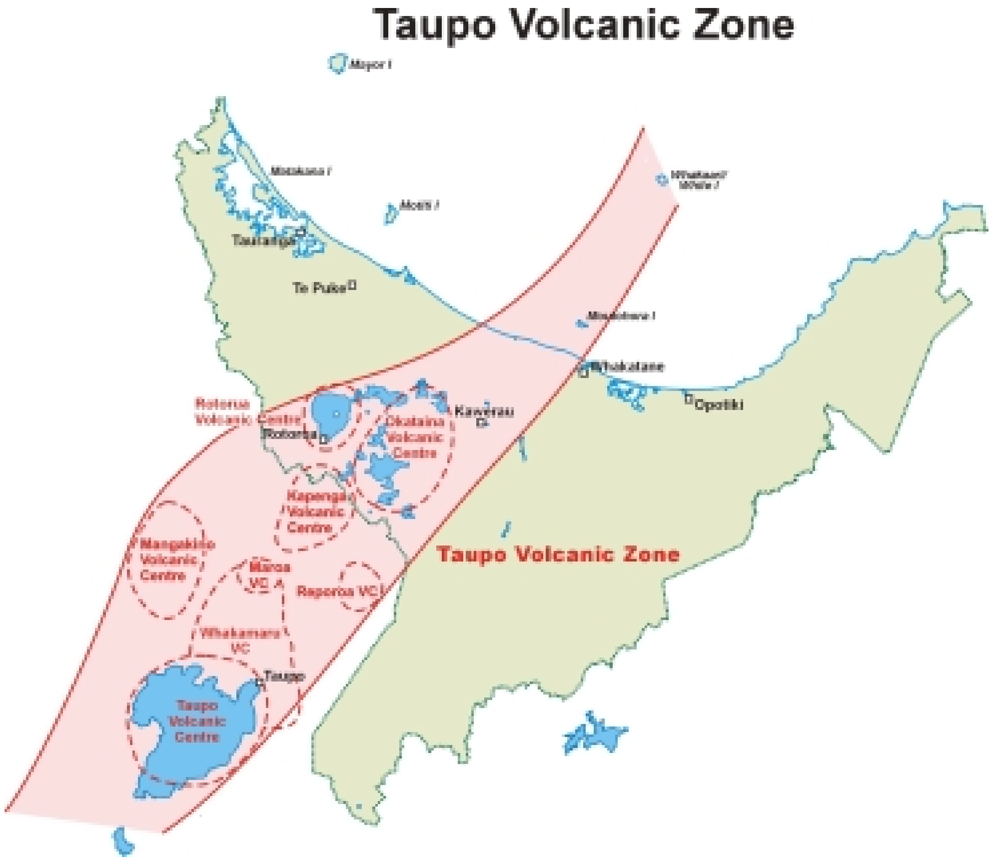


*Figure 3.1 Location of the Taupo Volcanic Zone and Rotorua volcanic centre (after Houghton et al., 1995).*

The shallow drill holes used to abstract geothermal water provides the largest database of the geology for the area. Although records are not systematic they do provide good stratigraphic information, but limited structural information. The three main shallow formations in the field that have been identified from this information are the Mamaku Ignimbrite, the Rotorua City rhyolite domes, and the basin sediments.

Rhyolite domes underlie the northwestern position of the city, outcropping in the northwest as the Pukeroa dome. Mamaku ignimbrite occurs in the east and south of the field, but it’s thickness is not well known because to date drilling has only penetrated less than 60m into the ignimbrite. Both the ignimbrite and rhyolite are overlain by lake sediments derived from a mix of muddy breccias, siltstones, pumice sand, and diatomites in various states of consolidation. Generally between 50 and 100 metres of lake sediments overlay the ignimbrite or rhyolites below, while up to 200m of sediments have been found in the Ngapuna area and in the southwestern side of Kuirau Park.

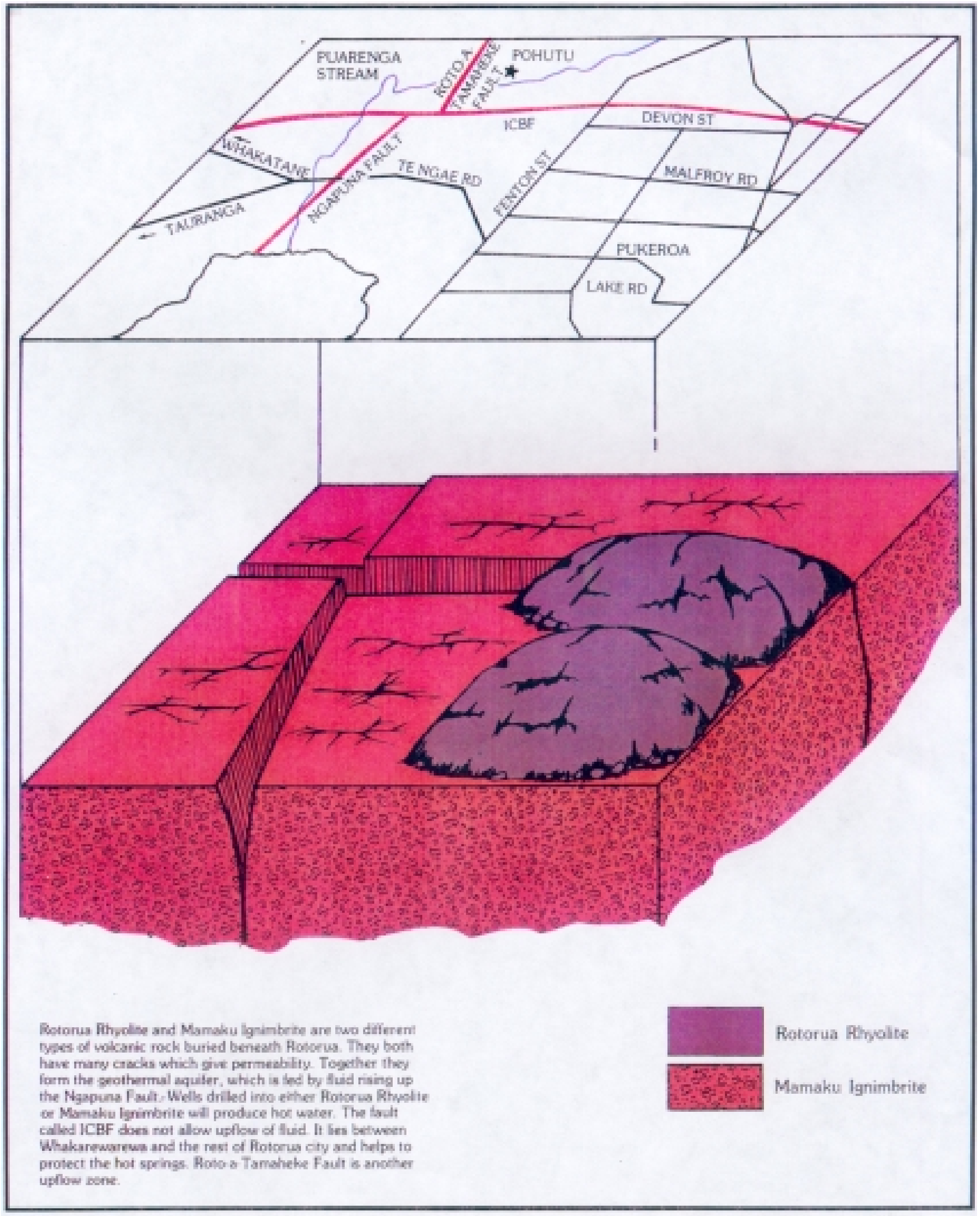
## 3.2 Structural Features

Thompson (1974) identified the boundary of the Rotorua basin caldera, but did not find faultlines within the caldera. However Lloyd (1975) identified and named a number of faults (Puarenga, Whakarewarewa and Pohaturoa faults) associated with hot springs at Whakarewarewa. Further work by Simpson (1985) defined the Roto a Tamaheke and Ngapuna Faults on the basis of fluid flow inferred from chemistry and enthalpy measurements on geothermal fluid.

Wood (1985) developed the concept of the Inner Caldera Boundary Fault (ICBF) to account for the abrupt change in elevation of the top of the Mamaku Ignimbrite in the area south of Sala Street. However, there is some uncertainty as to the exact position of the ICBF and this is discussed by Wood (1998). The lateral extent of the fault is also unknown (Wood, 1992) but this is due to the lack of data relating to extent rather than data relating to existence.

Wood (1992) also postulated the presence of another fault known as the Kuirau Fault. This fault is located in Kuirau Park and was identified on the basis of surface thermal activity, high downhole temperatures and the rhyolite surface morphology. Chemical and isotopic data of Stewart *et al*, (1992) confirms an up flow zone in the region of Kuirau Fault, which was identified by Wood (1992).

Despite this apparent confirmation of different techniques for inferring the presence of faults it should be noted that different techniques can place them in somewhat different positions. Chemical and isotopic data of Stewart *et al*, (1992) confirms an upflow in the region of Wood's Kuirau Fault. Taylor and Stewart (1987) used similar chemical and isotopic methods to place a fault where deep geothermal fluid upwells in the south east but west of the Ngapuna Fault, which was identified and placed by enthalpy and chemistry considerations. In the case of Ngapuna Fault the direct physical evidence is at odds with the chemical evidence, suggesting that there are lateral flows as well as vertical flows influencing the upwelling of geothermal fluid. These minor variations in placement are simply the consequence of using different techniques to infer similar features, and reflect the uncertainty in placement rather than uncertainty of existence. To this end a simple block diagram still provides a very good visual description of the major geological and structural features of the field (Figure 3.2).



Rotorua Rhyolite and Mamaku Ignimbrite are two different types of volcanic rock buried beneath Rotorua. They both have many cracks which give permeability. Together they form the geothermal aquifer, which is fed by fluid rising up the Ngapuna Fault. Wells drilled into either Rotorua Rhyolite or Mamaku Ignimbrite will produce hot water. The fault called ICBF does not allow upflow of fluid. It lies between Whakarewarewa and the rest of Rotorua city and helps to protect the hot springs. Roto-a-Tamaheke Fault is another upflow zone.

*Figure 3.2 Block diagram showing the major geological and structural features of the field (after Drew et al 1985).*

## 3.3 Hydrological Features

The flow of fluids in the field is constrained by geological structure and the physical properties of the fluid, for example:

- Pressure gradients are affected by local elevation and modified in some areas by surface drainage patterns;

- Natural surface features generally occur in areas where the structure provides an "easy pathway" to the surface;

Overall, the most reliable way to consider the hydrology of the field is to consider the evidence and then to decide on a mechanism that best fits this evidence such as:

- Data from resistivity surveys tend to show volumes with high temperature saline water;

- Magnetic anomalies indicate alteration products (in particular, magnetite is replaced by non-magnetic minerals) and can show both fossil and active systems;

- Heat flow surveys together with chemical flow budgeting indicate the flow of geothermal fluid and dilution by other water sources;

- Categorizing water into major groupings on the basis of its chemistry and isotopic analysis can be used to give information on the source of the water.

Glover (1974) compiled previous chemical surveys in the field, and provides a general summary of hot chloride water rising near Whakarewarewa. This flow mixes with a secondary flow arising near Pukeroa Dome and both are diluted with a low chloride ground water in the west and northwest, as they flow northwards. By 1985, Simpson (1985) and Wood (1985) have recognised the importance of structural controls on hydrology, and with the improved techniques of dilution maps (Glover and Heinz, 1985), and the techniques of isotope measurement (Stewart and Taylor, 1985), bores could be grouped by water type. The general model is of springs at Whakarewarewa fed directly by deep water of approximately 230ºC. This deep hot fluid also rises to the surface in the Ngapuna area and also flows north and west under Rotorua City.

By 1992, the detail of this model had improved due to refinements in measurement techniques and increased computing power. Nonetheless, different techniques again present somewhat different conclusions and the data are not sufficiently precise to enable choice between the shallow mixing and direct fluid upflow models. This discrepancy is most noted in the west of the field.

Giggenbach and Glover (1992) suggest that, on the basis of the chemistry of both water and gas that the fluid is derived from the basaltic, or associated rhyolitic sources of "spreading" tectonics, with a main hot fluid plume arising to the east of the field. This plume reaches the surface with little dilution by meteoric waters, and also feeds the Whakarewarewa area. A second, very much more altered plume of high bicarbonate fluid feeds the west. This fluid is cooled by long contact times, and diluted by meteoric water. Glover (1992) used a chloride budget to show that nearly

60% of the total output from the field is discharged through the lake bottom. The geothermal fluid appears to be of similar composition to the south-eastern fluid which would suggest that there is excellent hydraulic connection between the lake floor and the geothermal aquifer.

Stewart *et al* (1992) draws somewhat different conclusions as their model was derived from isotopic and chemical data from water and gas samples which suggests that the east-west flow is of shallower origin. They favour a boiling primary upflow in the east, extending from Whakarewarewa, through Ngapuna towards the lake. A portion of this outflow passes under the sediments that underlie the city, becoming diluted with bicarbonate-chloride water before mixing with cool ground water, and then discharging at Kuirau/Ohinemutu.

Graham (1992) in his study of rock-water interaction in the field based on strontium isotope ratios, suggests a deep origin for the primary water (of at least 2km) with direct upwelling in the east, and a flow to the west which undergoes dilution by old ground water, and interaction with the country rock.

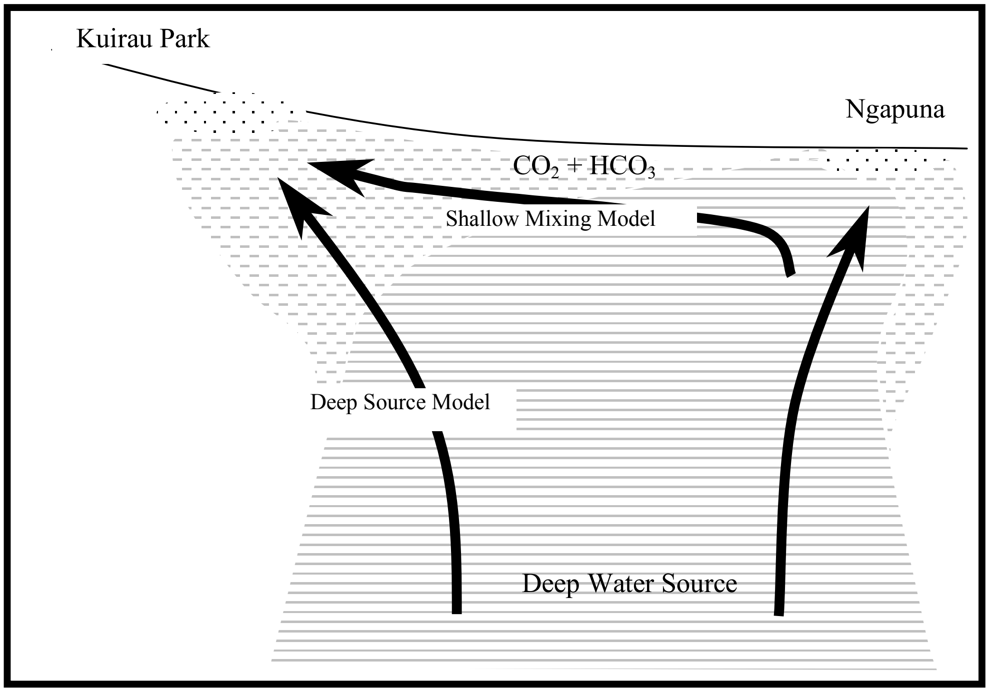


*Figure 3.3 Possible sources for near surface geothermal fluid in Rotorua – shallow mixing and direct deep source model.*

Glover and Mroczek (1998), by examining silica chemistry and using only the most reliable temperature data, suggest that there are two diluting fluids one at 150ºC and a second at 15ºC. Their data lends weight to the shallow mixing model.

Whatever the merits of the two models it is apparent that the two natural spring areas, in the west and in the east, are interconnected. With the east as the primary source, removal of geothermal fluid provides an alternate "exit" for the upwelling fluid, and provides fluid to the eastern natural features. For the natural features in the west, the mechanism is different, but the result qualitatively the same. The shallow mixing model gives interception of the fluids supplying the western features, while the deep upwelling to the west model will have the springs in the west affected indirectly by reducing the pressure at the deep source (Figure 3.3).

## 3.4 Chemical Characteristics

The processes of boiling, mixing, oxidation and wall rock reaction control the chemistry of the fluid. The extent to which these processes affect the geothermal fluid depends on the rate of the process, and the residence time of the fluid in the reaction zone. In the east hot alkali-chloride fluid is typical of deep fluid in New Zealand geothermal systems.

To the south, Arikikapakapa and Whakarewarewa geothermal fluids contain some bicarbonate but appear to have been diluted by cold ground water before boiling. In the north underlying Rotorua City is an area high in bicarbonate. A secondary high bicarbonate source occurs to the northeast at Kuirau Park/Ohinemutu which represents the deep chloride fluids diluted by shallower possibly steam heated fluids near surface groundwaters. These intermediate depth waters undergo changes as the fluid moves to natural features at the surface. Boiling, dilution, and oxidation tends to reduce the total carbonate species, all chemical concentrations and pH, while sulphate increases as result of oxidation. The best overall representations of the major chemistry of the water are the maps of Stewart et al (1992). Modified versions of these are given (Figure 3.4).

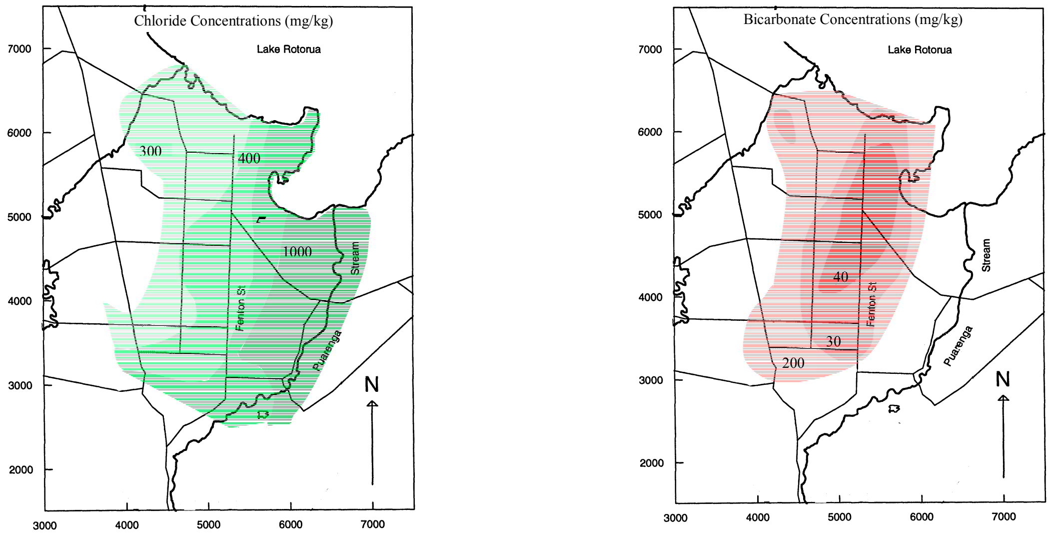


*Figure 3.4 Chloride and bicarbonate levels in waters from geothermal bores in Rotorua (after Stewart et al. 1992).*

## 3.5 Soil Gases

A consequence of the processes occurring during the migration of fluids to the surface is the loss of gases from the fluids. The most active processes are the separation of carbon dioxide and hydrogen sulphide. Finlayson (1992) measured the gases found in the soil (both pore gas, and adsorbed gas) in a very extensive survey of the field. Maps of the gas survey results show high $CO_2$ and $H_2S$ in areas that are supplied with hot geothermal fluid to surface, with local highs at Arikikapakapa, north of Whakarewarewa, and at Government Gardens (Figure 3.5).

Generally these soil gas highs overlie areas that contain hot geothermal fluid and, not surprisingly, do not bear much relationship to the soil temperature. A very notable feature is the absence of $CO_2$ or $H_2S$ in the Glenholme area, which overlies the rhyolite saddle. The geothermal fluid in this area contains moderate levels of $H_2S$, and total $CO_2$, while the pH is near neutral (Glover and Heinz, 1985). This suggests that either the capping or aquitard is robust in this area, or cold groundwater downflow sweeps out the gas before it rises to the surface.

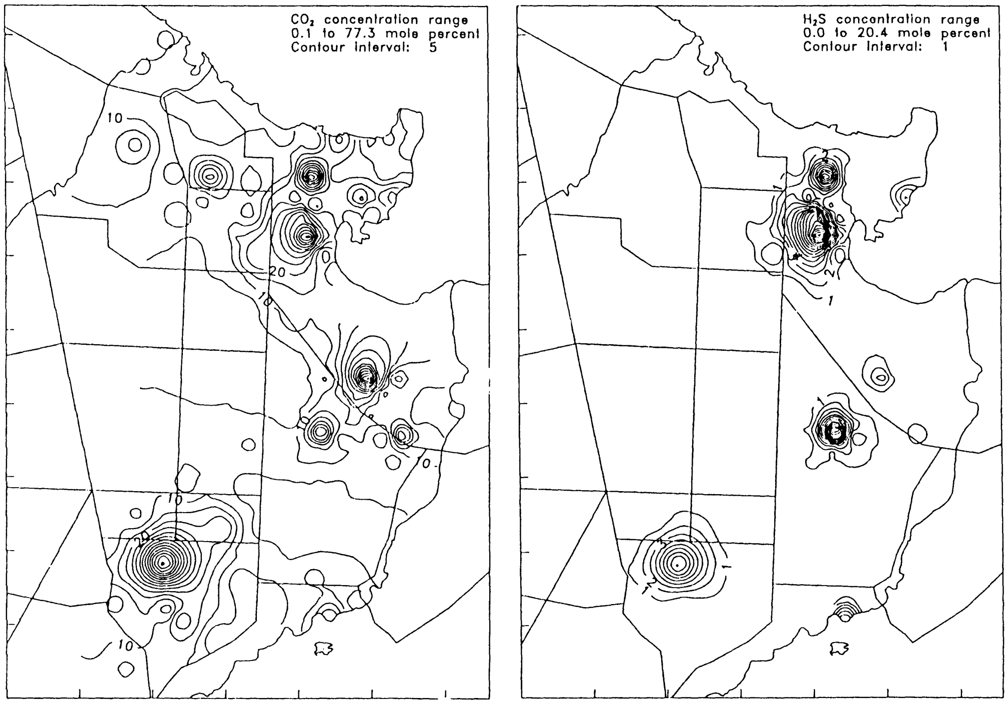
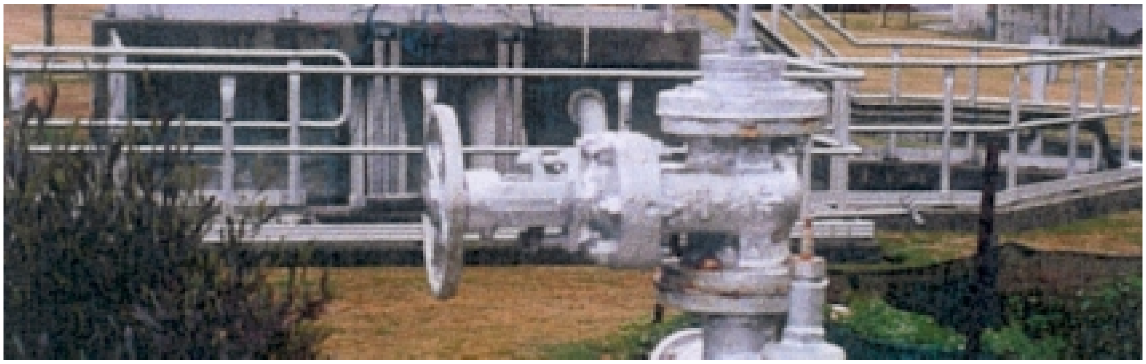


*Figure 3.5 Soil gas contours in surface soils at Rotorua (from Finlayson 1992).*

## 3.6 Surface Thermal Activity

The principle areas of activity included Ohinemutu (clear flowing springs), Kuirau (near neutral lakes and steaming ground), Government Gardens (alkaline chloride and weakly acid pools), Arikikapakapa (acid, generally cold lakes plus steaming ground) and Whakarewarewa (alkaline chloride near boiling, boiling and geyser features). The areas of thermal activity are shown in figure 3.6. The activity of natural feature geothermal activity is discussed in chapter 6.

*Figure 3.6 Areas of natural thermal activity in Rotorua Geothermal Field based on reported geothermal features. Areas of natural thermal activity in Rotorua Geothermal Field based on reported geothermal features (from Cody 2000). Natural thermal activity is generally confined to three areas of the geothermal field: Whakarewarewa/Arikikapakapa in the south, Kuirau Park/Ohinemutu (on the shore of Lake Rotorua) to the north and Government Gardens/Ngapuna /Sulphur Bay to the northeast that is also on the shore of Lake Rotorua.*



# Chapter 4: Monitoring of the Geothermal Aquifer

## 4.1 Introduction

Monitoring is a term used to describe ongoing measurement of field activity and behaviour, and the use of this data to define responses of the field to natural or man-made effects. This includes direct physical measurements of water level in both the geothermal and ground water aquifers, heat output and mass output from natural features, and measurement of interfering phenomena such as rainfall and barometric effects. This chapter discusses the measurements that are taken, and how the data is treated, as well as making an assessment of the uncertainties that are inherent in this particular monitoring programme. The actual data derived from the programme is discussed in subsequent chapters.

## 4.2 Monitoring Programme

Data collection in the Rotorua Geothermal Field began before the turn of the 20th century but was not well coordinated until the mid 1970s. Nairn (1974) collated much of the available data on the geology and extent of the field. Data collection continued under the vote-science funded system of DSIR in a large effort to describe New Zealand's scattered geothermal systems.

By the late 1970s the data being collected showed that the unconstrained withdrawal was affecting the field. In 1980, the government agreed to set up the Rotorua Geothermal Monitoring Programme for the field. There was a strong need to quantify the volume of fluid extracted from the field, and record changes in surface activity and geothermal aquifer characteristics.

The government monitoring programme began in 1982 and included establishing a network of monitoring bores to record water levels and temperatures in the geothermal aquifer and also geochemical investigations. Over the time period from 1982 to 1985, the Monitoring Programme was intended to:

- Develop an understanding of the hydrology and geology in the Rotorua Geothermal Field.
- Observe changes in the Field.
- Develop a numerical model of the field to aid management decisions.

This set of targets was met with the publication of the Technical Report (Ministry of Energy, 1985) covering geology, hydrology, surface expression (and variability), and the numerical model describing the effect of withdrawal on natural outflows. This major work was largely funded by Ministry of Energy, (the Government Department which at that time had responsibility for energy sources in New Zealand).

During the period of the Enforced Closure Programme, from April 1987 to July 1998 and in the following period to 1990, monitoring continued on a very intensive basis, funded largely by Ministry of Energy, with contributions from Rotorua District Council and the Bay of Plenty Catchment Board. The monitoring covered measurement of water levels in the geothermal bores, in the shallow ground water aquifer, and the natural output, (heat, mass, and chemical content) for most major groups of thermal features. The raw data, and processed data, together with interpretation and commentary was published in quarterly reports.

For the period from 1987 to 1990, the targets set for the monitoring programme were to:

- Monitor the recovery and performance of geothermal features and;
- To determine the nature and extent to which increased use can be made of the resource while ensuring conservation of the field.

During this time all the measured data sets indicated that the field appeared to have not reached a stable state.

By June 1990, control of the field had passed to the Department of Commerce while the Resource Management Law Reform Bill passed through its later stages. The Rotorua Geothermal Monitoring Committee, with members from Rotorua District Council, Ministry of Commerce, and Environment B·O·P, directed that monitoring should be focussed towards future management decisions by;

- Establishing a reliable database for field information;
- Identifying trends and relationships in monitored parameters;
- informing the controlling body of events that might warrant a review of field management practice.

Greatly reduced funding following the closure of the Ministry of Energy and the adoption of some of its functions by the Ministry of Commerce. This resulted in a very significant reduction in the data collected. Monitoring of water levels in the geothermal and groundwater aquifers and, some surface monitoring, continued with periodic "snap-shot" surveys of natural features. As before, this data was presented as quarterly reports.

In 1991 the Resource Management Act shifted responsibility for field management to Environment B·O·P. By 1996, it had become apparent that most of the recovery had occurred, and Environment B·O·P carried the entire financial burden of monitoring. This required the development of a regional plan to effectively manage the field. (The development Rotorua Geothermal Regional Plan occurred between 1991-1994). The Rotorua Geothermal Regional Plan became operative in July 1999 and has a broad target of information gathering and monitoring to enable reliable management decisions to be made.

The continuous collection of data has recently been augmented by an extensive set of surveys of natural features, and potential hazards, funded variously by the Earthquake Commission, Rotorua District Council, and Environment B·O·P.

The monitoring programme has settled primarily on measurement of geothermal bore pressures, and removal of interferences such as barometric, rainfall and ground water pressure effects. This data, together with occasional "snap-shots" of natural heat outflow, can be used on a continuous basis for examining the ongoing behaviour of the field, and on an occasional basis to calibrate and operate a numerical model of the field to test different management regimes.

## 4.3 Monitoring Data

Monitoring data is collected from a variety of sources. The very large 1982 to 1985 Monitoring Programme included contributors from Ministry of Works and Development Rotorua; Chemistry Division, DSIR Wairakei; Institute of Geological and Nuclear Sciences, DSIR Lower Hutt; Applied Maths Division, DSIR Wellington; Geological Survey, DSIR Rotorua; University of Auckland; and Pertamina, Indonesia. The current programme consists of monitoring aquifer water levels and temperatures and is undertaken by the National Institute of Water and Atmosphere (NIWA) Rotorua, under contract to Environment B·O·P. Industrial Research Limited, Wellington provides the data analysis service under contract to Environment B·O·P. From 1998 records and observations of significant geysers and springs have been recorded by Ashley Cody, Geothermal Consultant under contract to Environment B·O·P. This programme is currently under review to enable the development of more robust monitoring of key geothermal springs and features.

Figure 4.1 shows showing the monitoring sites across Rotorua City where data is collected at present.

## 4.4 Monitoring Bores

Monitoring bores known as the M-series bores are used to monitor the geothermal reservoir to depths of about 200 to 250 metres (Figure 4.1). Monitoring bores M1, M6, M12 and M24 tap the Rhyolite, while M9, M16 and M17 tap the Ignimbrite aquifer. The water level data for these bores is automatically collected and recorded at 15 minute intervals, and temperature profiles are measured usually once per year. Since 1998 there have been variations to the data collection schedule as different sensor methods are used in order to maintain an up to date system.

A network of shallow ground water bore at depths up to 10 metres known as the G-series bores are used to monitor the shallow groundwater levels and temperatures. Measurements are usually taken at intervals of up to two weeks (Figure 4.1).

Continuous air pressure and rainfall data is captured so that the interferences due to barometric pressure can be removed from monitor bore data, and the influence of large rainfall events identified.

Figure 4.1 Current geothermal and shallow groundwater monitor sites in Rotorua.

Lake Roto-a-Tamaheke outflows were measured at "Bath" and "Path" sites to attempt to quantify the thermal output of the largest feature in the Whakarewarewa area. However, the outflows from the lake and its surrounding springs are altered by human intervention and consequently monitoring data from these sites is of dubious quality. As a result monitoring these sites has been discontinued.

Prior to the present monitoring programme a more extensive (and expensive) monitoring programme recorded the heat and mass outflow from the Whakarewarewa area into the Puarenga Stream. Analyses of the waters from some natural features in the Whakarewarewa area were also recorded. This portion of the programme was abandoned on the grounds of poor return for cost, with the knowledge that single event (snap-shot) monitoring could be taken to assess longer term trends. For the Puarenga Stream increment, sensitivity of the measurement to small calibration changes, and the small changes made interpretation of the data rather equivocal in the short term, although long term changes were clearly visible. In 1997 this data collection segment was discontinued. The chemistry of natural discharges, and of bore waters, shows the changes in the processes where fluid reaches bores and natural discharges. This was a costly segment of the programme, and in 1993 was terminated in favour of "as required" analyses. This means there is some risk as the chemical data can only be used to confirm other trends that might cause an alert, rather than the chemical data alone giving rise to an alert.

### 4.4.1 Bore Pressure

The pressure in any aquifer can be expressed as an equivalent head, equal to the height of a column of water than can be supported by a known pressure. This water level is equal to that of the height of the top of the water column in the bore. This is perfectly accurate if, and only if, the water temperature in the bore does not change. It does not matter whether the temperature varies up the column or remains constant with time, but only becomes untrue if the temperature varies at any vertical position in the column with time. It has been a point of much criticism of the monitoring programme that such a change with time could occur between the annual temperature profiling and vitiate the data between the calculation of the profiles (See for instance, Rotorua Bore Users Association Inc (RBUA) (1994), and Just (1998)).

In 1992 and 1993 experiments were carried out to test the relationship between pressure and corresponding water levels in two monitor bores. Water levels were measured in two bores (M6 and M12) and the pressure was measured directly by a gas pressure system (in the same bores, but designated M22 and M24 respectively). Plots of these well pairs and the residuals for the corrected data sets have been scaled and shifted vertically to allow comparison (Figure 4.2). It is very clear from the plots that the differences between pressure and level are much smaller (by a factor of about 15) than the variation. These experiments show that water levels provide a reliable way of monitoring deep geothermal pressures, and the collection of temperature profiles gives an additional check on the validity of the data.

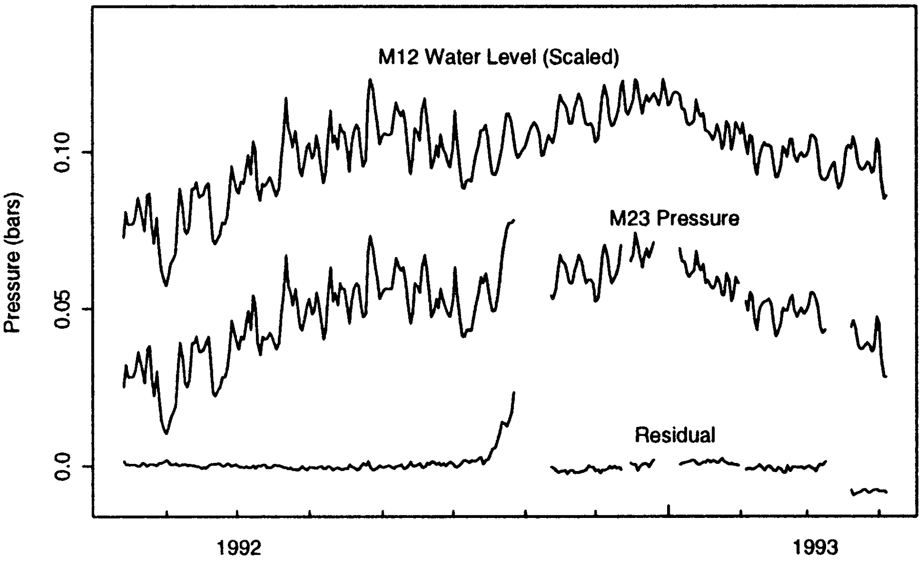


*Figure 4.2 Pressure-level relationships for two well pairs.*

### 4.4.2 Barometric Variation

Typical daily variations in barometric pressure may be as high as 10mbar(millibar) while weather pattern fluctuations will bring still higher pressure variations. A variation of 10mbar will cause a 0.1m change in water level, which is significant when compared with annual fluctuations in water level of about 0.7m. These barometric effects are removed from the water level data to show the finer detail of the water level changes in the geothermal aquifer.

### 4.4.3 Natural Features

The monitoring programme began as a result of the perceived need to protect the natural features of the area, especially those in the south of the city. It is very difficult to find a way to monitor the behaviour of natural geothermal features in a way that will give some indication of changes on a short timescale. It is possible to measure longer term trends, and to compare the behaviour or changes on a timescale of months or years. During the 1982-1985 intensive monitoring phase, chemical (Glover and Heinz 1985), temperature, and flow (Cody and Simpson 1985), and the isotope hydrology data from springs and bores (Stewart and Taylor 1985) were collected, and descriptive material from public sources. Collection of chemical data for the larger features continued until 1993 but was prone to discrepancies due to rainfall and weather influences that trended over the time scale of a few years. New assessments of the heat and mass increment to the Puarenga Stream from Whakarewarewa were carried out in 2001 to compare current values to the earlier 1967 and 1984/1985 surveys to detect longer term trends. The analysis of this data is discussed in chapter 6.

## 4.5 Risks and Benefits in Monitoring Programme Data

The collection of data intended to support decisions in the management of natural features brings difficulties not normally associated with the more usual type of data collection designed to determine the gross response of a geothermal field where fluid is abstracted for electricity generation. This is because natural features have such a large natural variability, and because natural features can only be modelled in an approximate manner. Therefore it is very difficult to determine if changes are part of natural variation, or part of a response to abstraction from the field. Nevertheless, it was apparent by 1985 that the reduction in pressure in the Rotorua field was due to abstraction of fluid from domestic bores, resulting in a decrease in natural geothermal activity.

### 4.5.1 Field Pressure and Temperature Monitoring

During the late 1980's improvements in data logging equipment meant that the most reliable way of collecting pressure data was to measure water level and to then correct this to pressure using the temperature profile in the bore. Although this has been widely criticised on the basis of infrequent temperature measurement, (RBUA, 1994) and the risk of changing temperature profiles causing uncertainty in the pressure in the bore between temperature profiling, such criticisms are poorly founded. Temperature profiling has shown little variation in the bore temperatures. This is demonstrated by a series of measurements by NIWA who measured pressure directly in the same bore as the water level in the period 1992 to 1993. Analysis of these measurements showed that there is little difference between the two records (Kissling, 1994).

The risks associated with assuming a strong correlation between pressure and water level are small while the field is stable but in an unstable field, the risks would increase. As part of the Environment Court settlement of 1998, Environment B·O·P was required to put in place a trigger level for the three M series monitor bores (M6, M12 and M16) with a good data level record. If water levels drop below the trigger value in any one bore a set of remedial actions are put into place.

Data for rainfall and barometric effects can be collected reliably and to an accuracy that exceeds that required for their use in this programme. Rainfall and barometric data are used to remove effects of perhaps 20% of the size of the annual variation, so there is little risk associated with this data and its quality.

### 4.5.2 Natural Feature Outflow Monitoring

Stream gauging is used to assess both outflows from natural features and also to assess the flow in Puarenga stream before and after the increment from geyser flat meets the stream. The geyser flat increment is measured as the small difference between two similar values, and depends very strongly on the gauging calibrations at both points. Changes between measuring techniques have resulted in slightly different values for the flows, and these inconsistencies have never satisfactorily been resolved. However. the data could be managed by normalising it across the period where ratings changed. This data segment is no longer collected, so there is a risk that in restarting this data set the ratings may not be compatible with the immediate previous set, and the Geyser Flat increment may not be directly comparable with previous values.

### 4.5.3 Field Chemical Data

Chemical analysis of the water is used in two distinct ways. The first is as a method of grouping features (natural or manmade) into groups based on their chemistry and hence on the source of their water. Conceptual models of the field involving near surface interactions with oxygen rich groundwater, or with other water supplies can then be invoked for the second major use of water chemistry, which is defining the processes that occur as geothermal water moves through the aquifer. Generally, the composition of deep geothermal water changes little with time, but the processes that the water undergoes vary dependent on the relative pressures driving the flows of mixing water and geothermal water. Collection and analysis of fluid is regarded as routine (given that they are sampled and analysed with due care), so there is little risk of the analyses being incorrect.

The conceptual model for Rotorua Geothermal Field is far from complete, especially the east to west subsurface flows in the northern part of the city. The best available data still does not entirely define the processes that occur. Up to about 1993, chemistry in the field had generally stabilized, apart from small variations in the chemistry of discharges from natural features. This program segment was terminated in 1993 on that basis. Nonetheless, the chemistry of discharges is still used on an occasional basis to define processes that have occurred which are not within the expected range of behaviour. Its use as a second tier tool means that chemistry can be used to explain changes, but not to predict or give early warning of them. It seems that there is some risk associated with this stance, but to be sure of capturing the precursor to an event, the chemistry of discharges would need to be measured and assessed on a continuous basis, which would clearly be a very expensive proposition.

# Chapter 5: Field Aquifer Monitoring Results

## 5.1 Introduction

This chapter describes the data that has been measured in the field, and the processes that it undergoes to remove barometric and other extraneous effects. Once the data is corrected, it can be examined to determine which effects are within "normal" variability, and which effects show characteristics that are likely to be due to "abnormal" events, (such as abstraction of fluid, and changes in heat and mass flows).

## 5.2 General Features of the Monitoring

The data can be conveniently broken into three phases:

- The exploitation period up to mid 1986 was dominated by abstraction of geothermal water when peak abstraction of nearly 30,000 tonnes per day occurred;
- The closure phase from 1986 to the end of 1992 that includes the voluntary closures, enforced closures and immediate recovery;
- The post-closure phase of field equilibrium and surface feature recovery from 1992 to 2000, that was dominated by the greatest recovery of surface features and variations in natural outflow.

In the following discussion each data set is presented in its entirety from the earliest records during the 1980s, to the present, or to cessation of data collection. The data is discussed in terms of the three identifiable phases. The data sets are considered in the following order: monitor wells, groundwater wells, mass, chloride, heat flows and other natural features.

### 5.2.1 Monitor Wells

The most recent data set is that of Kissling (2000). Data for monitoring bores; M1, M6, M9, M16, M17 and M24 have been adjusted for barometric influences shown in figures 5.1-5.8. Data for the entire period has been run as a single data set, so that long-term trends can be assessed. Where wells have failed, terminating the data set, the records are taken from the earlier publication of Bradford (1990).

*Figure 5.1 Water level in M1 with barometric pressure removed (from Kissling 2000).*

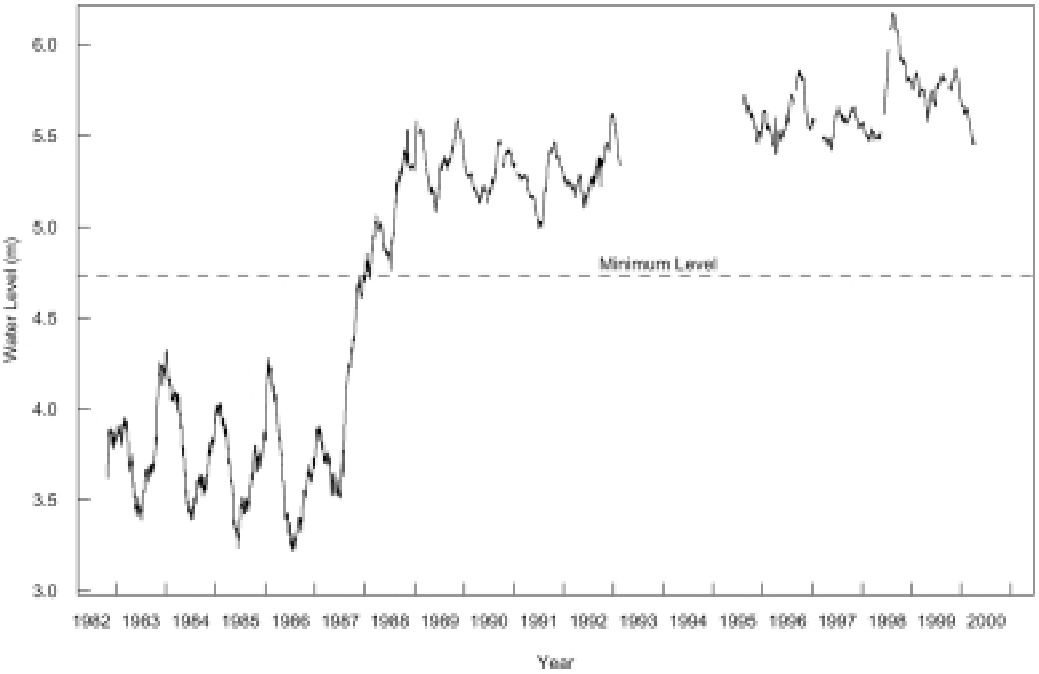


*Figure 5.2 Water level in M6 with barometric pressure removed (from Kissling 2000).*

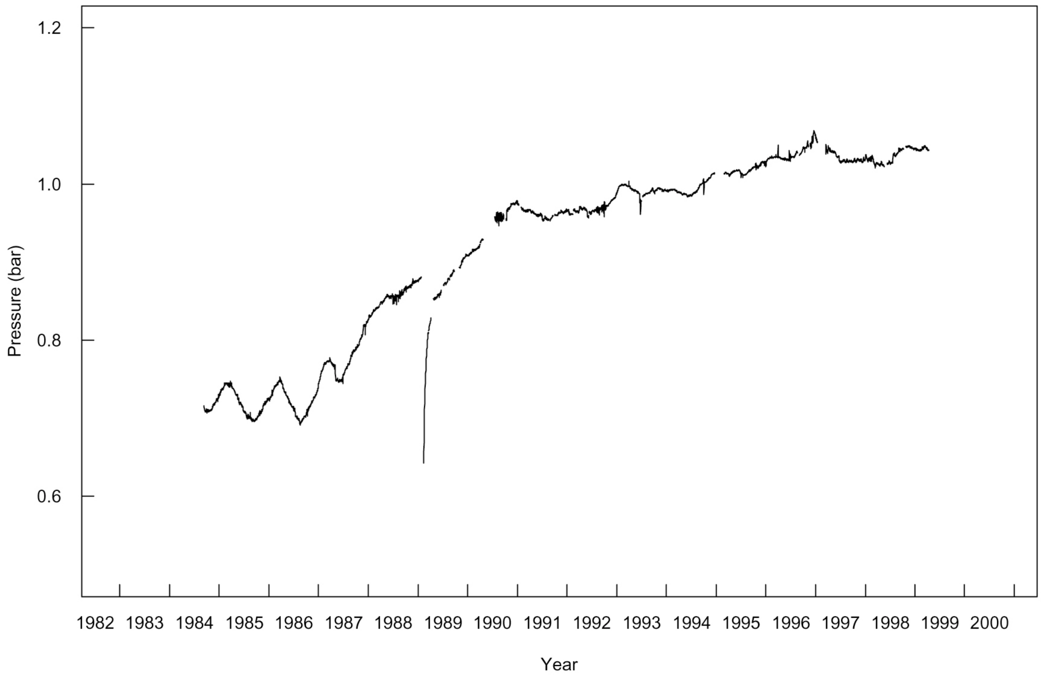


*Figure 5.3 Water level in M9 with barometric pressure removed (from Kissling 2000).*

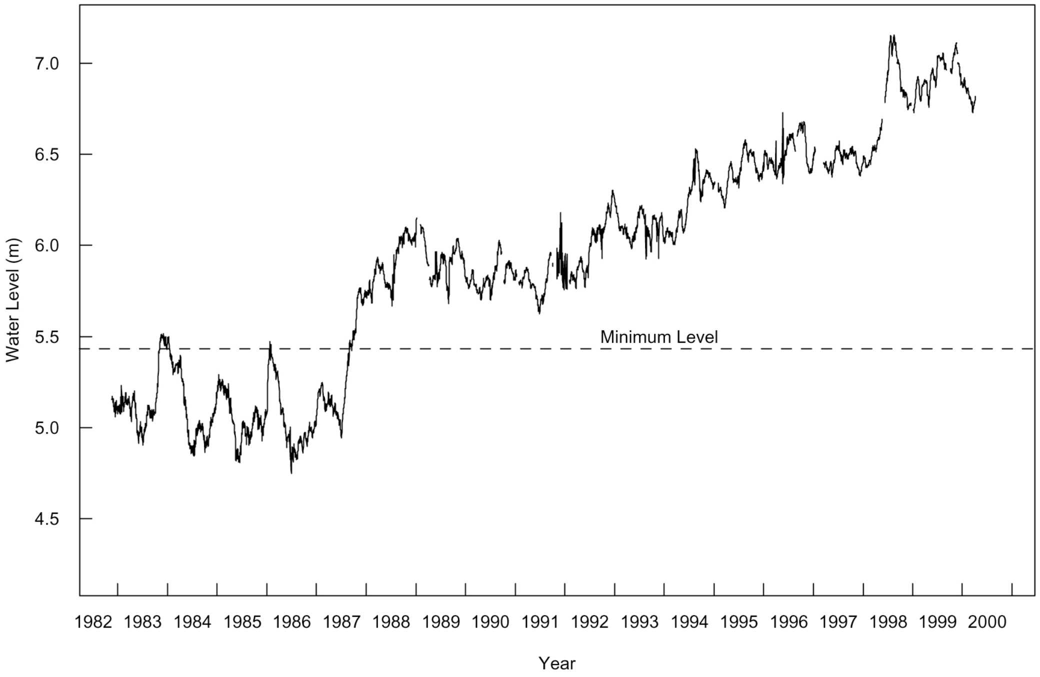


*Figure 5.4 Water level in M12 with barometric pressure removed (from Kissling 2000).*

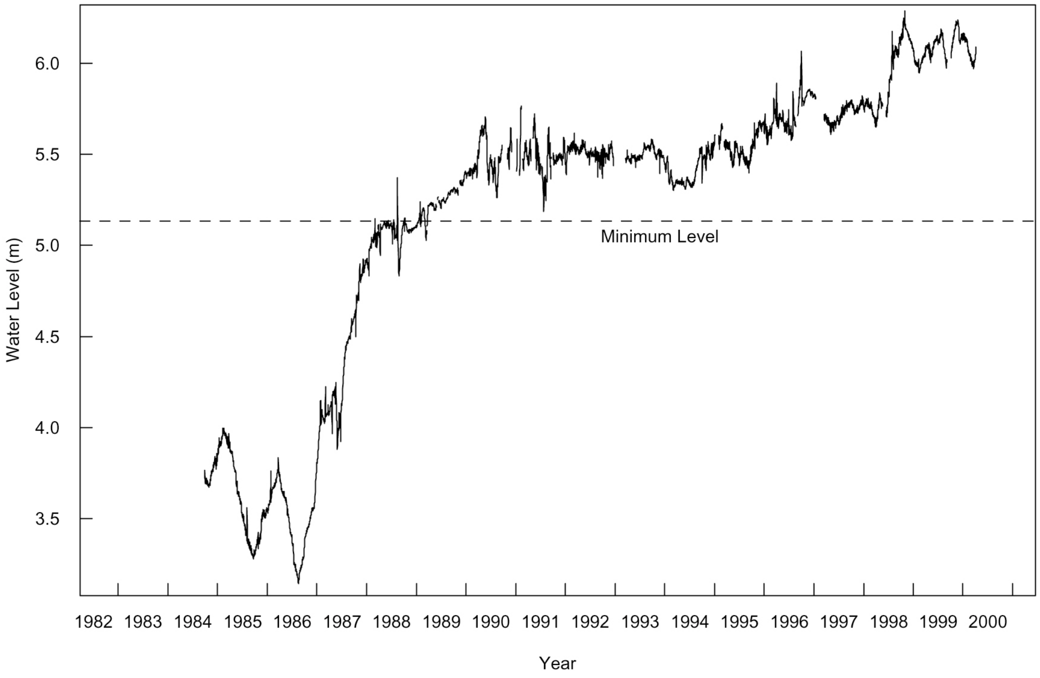


*Figure 5.5 Water level in M16 with barometric pressure removed (from Kissling 2000).*

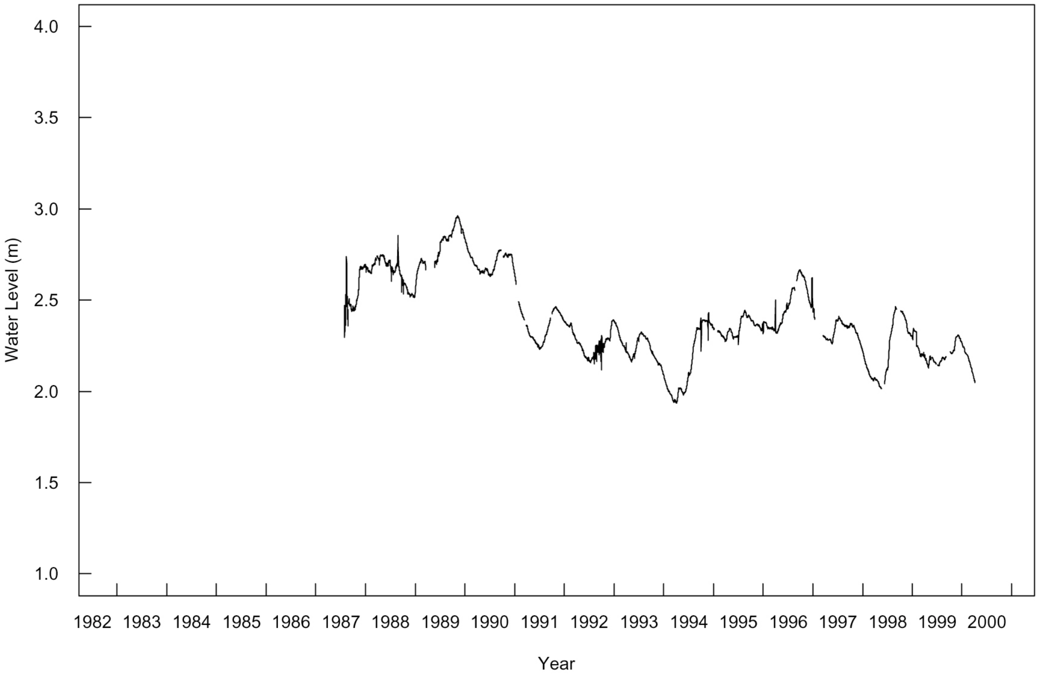


*Figure 5.6 Water level in M17 with barometric pressure removed (from Kissling 2000).*

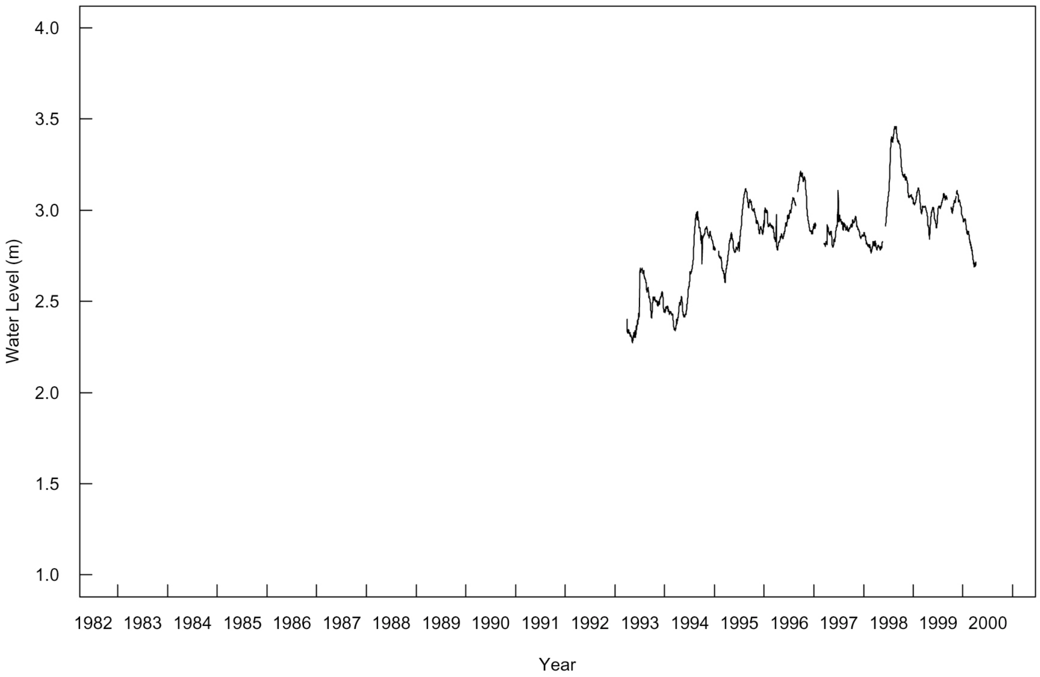


*Figure 5.7 Water level in M24 with barometric pressure removed (from Kissling 2000) .*

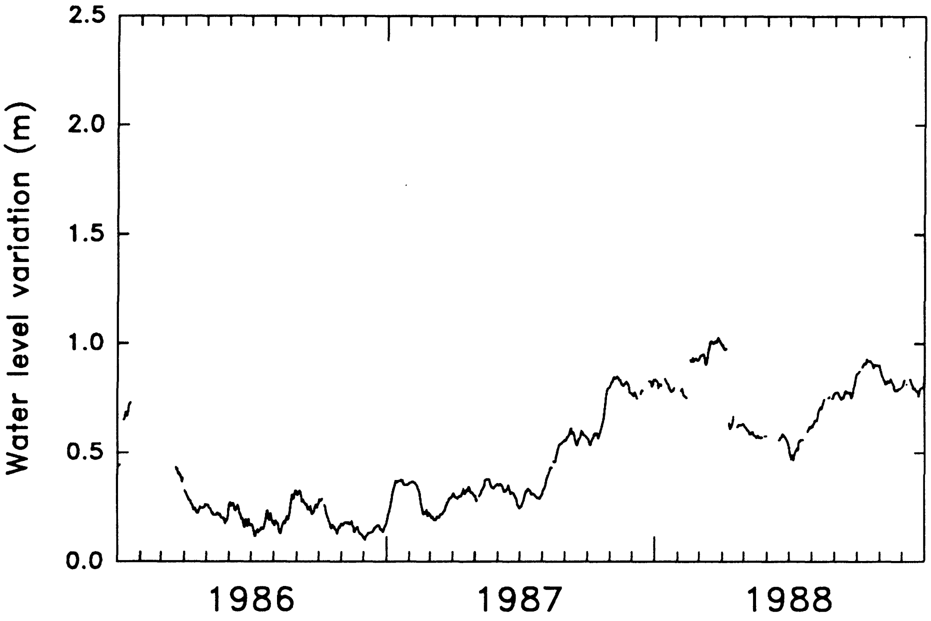


*Figure 5.8 Water level in M3 with barometric pressure removed (from Kissling 2000).*

5.2.2 A general description of geothermal monitoring bores is given in table 5.1.

*Table 5.1 Locations, drilled depth, approximate recent height of water-level, and dates of measurement for the Monitor bores and ground-water sites. Lake Rotorua data is for the present site. RR numbers are given for comparison with other data sets.*

| Monitor Wells in Rotorua | | | | | | |
|---|---|---|---|---|---|---|
| **Name** | **RR No** | **Location** | **Depth (m)** | **Water-level (masl)** | **Data from** | **Data to** |
| M1 | 305 | Government Centre | 64.0 | 289.4 | 5 Nov 82<br>1 Oct 83<br>15 Jul 97 | 23 May 83<br>17 Jul 85<br>present |
| M3 | 462 | Queen Elizabeth II Hospital | 140.2 | 281.5 | 13 Dec 82<br>17 Mar 86 | 19 Jan 86<br>22 May 89 |
| M5 | 684 | Carnot Street | 175.3 | 276.5 | 21 Oct 82 | 25 Oct 85 |
| M6 | 777 | Goodwin Avenue | 256.0 | 280.6 | 29 Oct 82 | present |
| M9 | 889 | Sewage Farm | 244.5 | 294.5 | 28 June 94 | present |
| M12 | 886 | Rotorua Public Hospital | 75.0 | 284.4 | 17 Nov 82 | present |
| M13 | 868 | Forest Research Institute | 97.3 | 291.8 | 19 Apr 83 | 2 Oct 86 |
| M14 | 409 | Racecourse | 70.1 | 283.8 | 15 Nov 83 | 27 Sep 85 |
| M15 | 883 | Victoria Street | 134.0 | 278.0 | 2 Dec 83 | 7 Aug 87 |
| M16 | 624 | Sala Street | 156.9 | 296.0 | 25 Sep 84 | present |
| M17 | 724 | Waiariki College | 156.1 | 296.3 | 7 July 87 | present |
| G14 | | Racecourse | 10.0 | 283.5 | 8 Sep 82 | present |
| Lake | | Mission Bay | | 279.8 | Mar 74 | present |

The period to mid 1986 was characterised by very strong seasonal cycles, with lows during the months of May/June, and highs during the months December/January. There is remarkable consistency between monitoring bores in the timing of these extremes. A consistent decline in pressure is evident in bores M3, M5, M6, M12, M13, M14 and M16. This decline is not evident for bore M1, while M9 exhibits increasing annual range. M1 had only small portions of record, while the data for M9 has never been satisfactorily explained. For all monitoring bores, the water level was consistently showing a seasonal variation (low in winter, high in summer) about a decreasing value.

Over the period beginning in the latter part of 1986, and extending out to the early part of 1989, there was a general increase in level for all bores where data is available. For M6, M12, and M16 the slope of this increase is very close to that for the annual increase shown in the previous period. For monitor bore M9 this slope of the increase is much lower, taking nearly twice the time to respond compared to other bores. For M1, M17 and M24, the monitoring data does not cover this period.

From 1990 to 2000, both the short and long-term behaviour of the water level has changed. Monitoring bores M1, M6, M9, M12, M16 and M24 have shown a consistent long-term rise in the water level (Figures 5.1-5.8). However the onset of this rise in monitoring bore M6 (Figure 5.2) was delayed until about 1993, and the long-term rise is only about one third of the increase during 1987-88. For monitor bore M9 (Figure 5.3), the rise was continuous with a slow change from 1987 to 1991, but is less than half of that increase. M12 (Figure 5.4) and M16 (Figure 5.5) have shown similar changes to M6 (Figure 5.2), but the magnitude of the rise in M12 (Figure 5.5) is about the same size as the 1987 to 1990 increase. Monitoring bore M16 increased from 1994 to present, the magnitude of this rise is about one third of the 1987-1990 increase.

The short-term variations in water level have also changed. The annual peaks are, generally, less than half their pre-1987 value, and displaced in time. Prior to bore closure, water level lows occurred in the winter months of the year. This is apparent for all years from 1982 to 1986. After bore closure water level lows occurred in the summer months and have a much smaller magnitude than the previous lows. It is likely that the annual variation in monitor bore level prior to closure was strongly imprinted by the annual variation in geothermal fluid withdrawal.

Rainfall has significant effect on the levels in the monitor bores. Figure 5.9 and 5.10 (from Kissling, 2000), shows the yearly and monthly averages respectively for rainfall from 1979 to 2000.

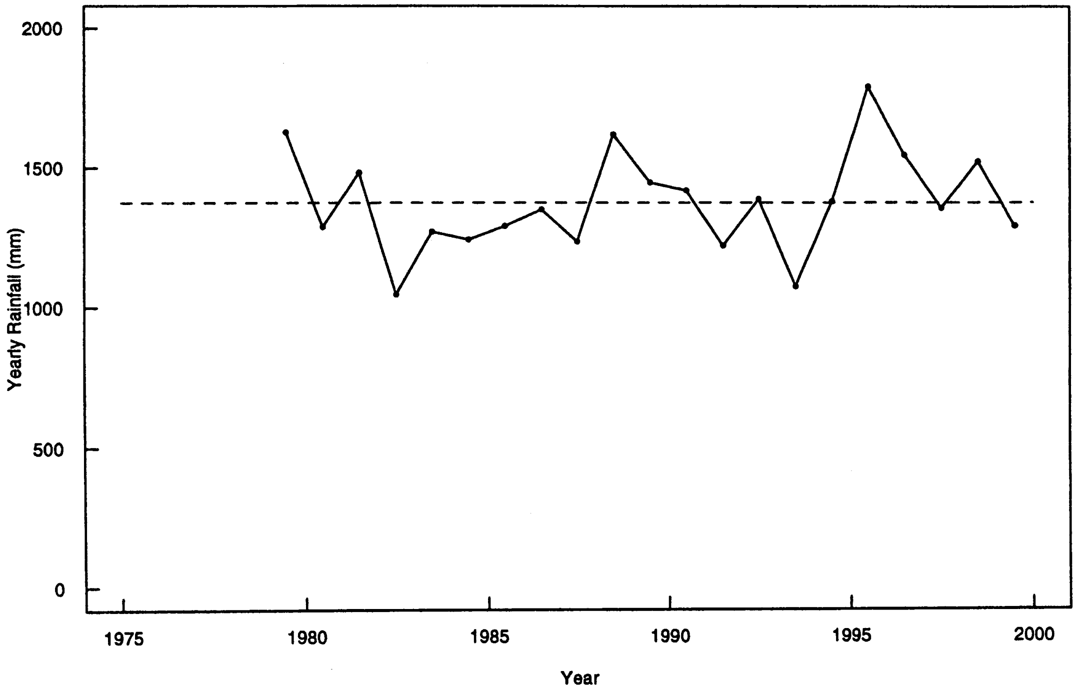


*Figure 5.9* *Average annual rainfall in Rotorua from 1979 to 2000 (from Kissling, 2000).*

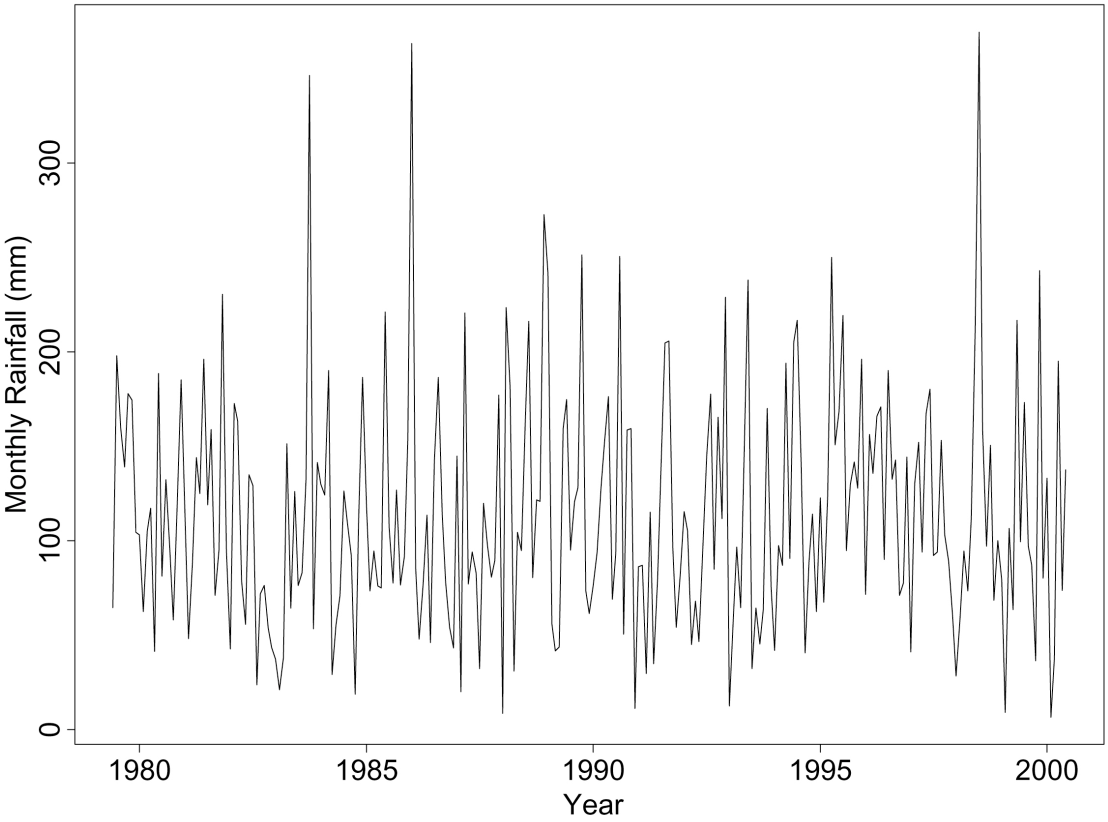


*Figure 5.10 Average monthly rainfall in Rotorua from 1979 to 2000 (from Kissling, 2000).*

Rainfall increases the level of Lake Rotorua, and increases the level in the ground water bores. Bradford (1992) has shown that pressure is transmitted between ground water and geothermal bores, with some strong and some weak correlations. On the basis of a chloride budget for the field, Glover (1992), found that there should be very good hydraulic connection between the geothermal aquifer and the lake.

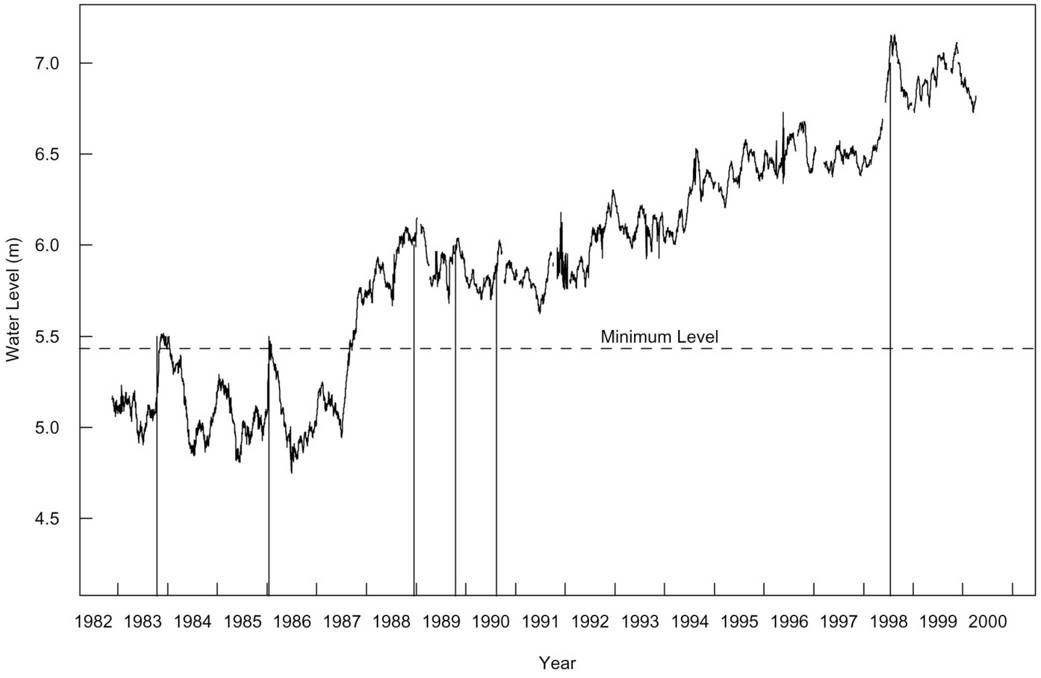


*Figure 5.11 Rainfall events in the record of M12 (from Kissling, 2000).*

The rainfall records show high rainfalls in December 1988, October 1989 and August 1990, and very large rainfalls in October 1983, January 1986 and July 1998. The water level record for M12 (Figure 5.11) shows that all these high rainfall events are followed immediately by highs in the monitor bore level, which are then followed by slow decay over 2 months. Most of these high rainfall and corresponding high water level events are evident in the data record of other monitoring bores.

The overall interpretation of the geothermal bore water level monitoring data is:

1. **The exploitation period up to mid 1986**

   During the period to mid 1986, the geothermal aquifer shows a level driven largely by the high winter drawoff with decreased summer withdrawal permitting partial recovery on an annual basis. The rainwater signal, transmitted to the geothermal aquifer by the ground water aquifer modifies this response, but is not strong enough to override the pattern caused by withdrawal. The ratio of winter to summer withdrawal for 1985 was assessed as 31,000 t/d: 25,000 t/d (Drew, 1985). This annual pattern is overlaid by a downward trending average in almost all monitoring bores, suggesting that overall pressure was falling, with the field unable to compensate for the overall withdrawal. The response was not caused by rainfall.

   Turner (1985) used historic failures of major Whakarewarewa springs to demonstrate that lows in geothermal activity are likely to have followed lows in rainfall in the proceeding 8 years. Bradford (1990) suggested that Turners model should place less reliance on running means of rainfall. This is because only large rainfall events (greater than 40mm rainfall) are important for recharge, and the seasonal variation of evaporation is a significant control on ground water storage (Kissling, 1997). Therefore Turners model seems to be poorly based.

## 2. Closure and recovery period 1986 to 1992

Bore closure commenced in 1986 with the most of the closure occurring through 1987 as the enforced closure programme came into action (Figure 5.12).

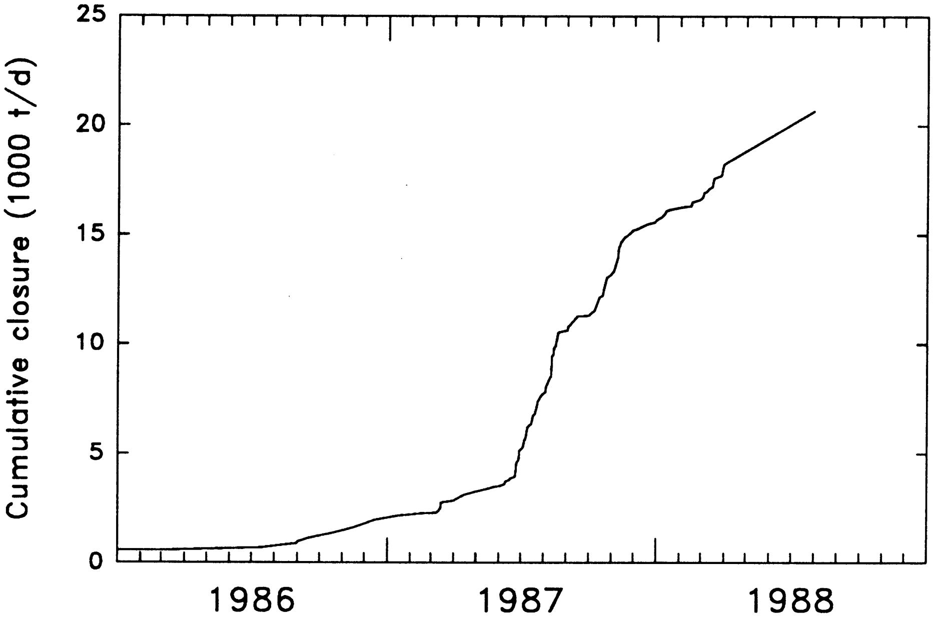


*Figure 5.12 Progressive closure (after Bradford 1992).*

Over the closure period a significant pressure increase occurred, much larger than changes caused by seasonal fluctuations. Monitoring bores can be separated into two groups based on the ratio of; the water level response from bore closure to the seasonal response prior to bore closure. These two groupings coincide with the two predominant aquifer types (Table 5.2).

*Table 5.2 Seasonal variation, and level rise due to closure for M-series monitor bores.*

| Well | Seasonal | Closure | Aquifer type | Ratio |
|---|---|---|---|---|
| M6 | 0.7m | 1.8m | rhyolite | 2.6 |
| M9 | 0.04b | 0.17b | ignimbrite | 4.2 |
| M12 | 0.4m | 0.8m | rhyolite | 2.0 |
| M16 | 0.5m | 2.0m | ignimbrite | 4.0 |

For the monitor bores in the ignimbrite aquifers the response was greater than for the bores in the rhyolite aquifers (Table 5.2). It seems that the monitoring bores in the rhyolite are either showing a lower response to bore closure or bore closures occur predominantly in the ignimbrite where abstraction has caused greater local draw down. These propositions are not testable with the data available.

## 3. Post-closure phase 1992 to 2000 - surface feature recovery

Since closure there has been a predominant rising water level trend in most monitor bores of about 1m. This cannot be accounted for as rainfall variation rises, due to closure or changes in usage. This rising trend commenced in 1992 for bore M1 and 1995 in M16, (Monitor bore M17 ran against the trend with falling water levels, the reason for this is not clear). This trend is accompanied by an abrupt rise in May-July 1998. The abrupt rise of July 1998 appears to be due to high rainfall in the previous months (Kissling 2000), but the longstanding nature of the rising trend suggest that it is unlikely to have been caused by rainfall alone because:

- The annual rainfall over the past 20 years has scattered around a stable average value. This has followed a falling trend in rainfall from 1960 to 1980 (Figure 5.13) (Bradford, 1990);
- The short timescale (approximately one month) of the response to rainfall would suggest a variation in monitor bore water level dominated by rainfall highs, and generally following rainfall.

The rise in water level also exceeds in most cases the rise due to closure (given in Table 5.2). It is simply not possible for the rise to be due to extra closure. In 1989 net withdrawal was about 22% of the 1985 value and by 1992 this had fallen to 15% (O'Shaughnessy and Grant-Taylor, 1992).

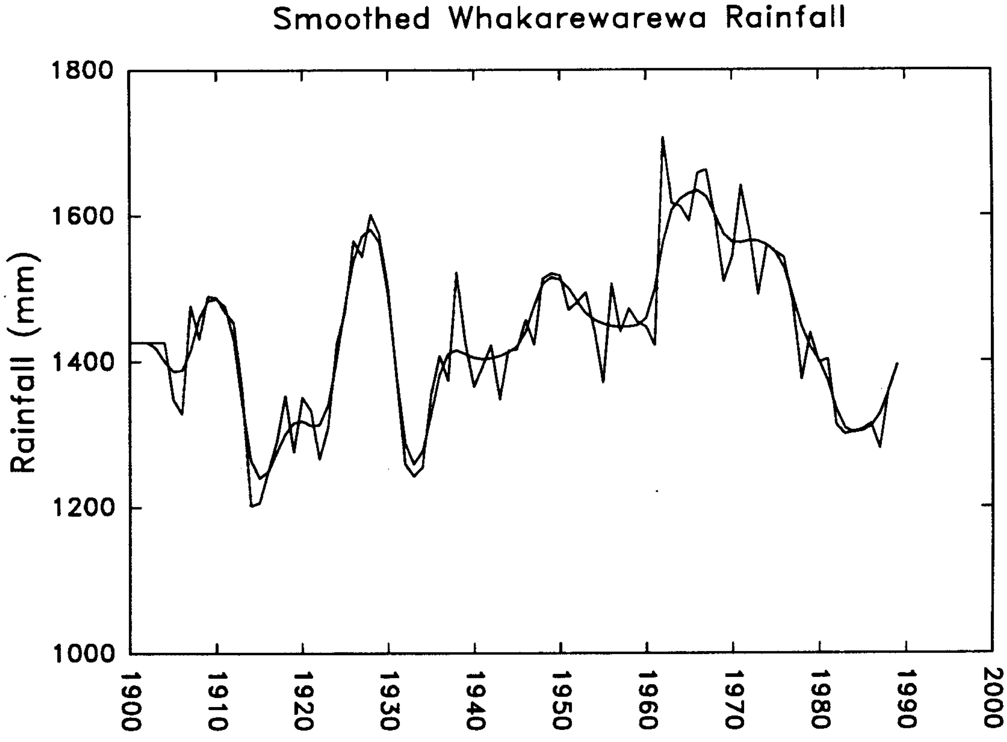


*Figure 5.13 Smoothed annual rainfall trends at Whakarewarewa 1900-1990. Note the annual falling trend in rainfall from 1960 to 1980 (from Bradford, 1990).*

A possible explanation of the rise is an increase in the total output of the Geothermal field. Kissling (1998), has shown that it is quite possible for heat and mass output to vary by several percent on timescales of decades. Although it is possible to speculate on the mechanism of the rise, the data is strong enough to confirm the presence of the rise and to show it is not an artefact of any of the more common influences on geothermal field pressure. This brings an interesting corollary. If, as some of the monitoring bores suggest, the rise started very early on in the monitoring programme, with the early part of the rise obscured by the downward trend in the late withdrawal period, and the strong rise of the closure phase, then the true impact of withdrawal would have been larger against an assumed background of constant field outflow.

The rate of increase and possible onset of the slow increase in the monitor bores is shown in table 5.3. This somewhat subjective analysis shows that the onset first began in M1 and M6 and did not occur in M16 until 5 years latter.

*Table 5.3 Onset of rise, and rate of rise, for slow increase in geothermal monitor bore water level/pressure.*

| Well | Region | Onset | Rate m/y |
|---|---|---|---|
| M1 | Rhyolite | 1990 | 1.0m/8y |
| M6 | Rhyolite | 1990 | 0.5m/15y |
| M9 | Ignimbrite | 1991 | 0.2b/12y |
| M12 | Rhyolite | 1993 | 1.0m/7y |
| M16 | Ignimbrite | 1995 | 1.0m/8y |

There appears to be no geographical relationship to the slow increase, especially when it is noted that normally M9 responds slowly and in a strongly damped manner to most disturbances, but was one of the first to exhibit the slow increase. The increase is much more general than the faster response to closure, and unrelated to the aquifer type.

## 5.3 Temperature Profiles in the Monitor Wells

Figures 5.14 to 5.19 show the temperature profiles since 1992 in the geothermal monitor bores, together with the boiling point-depth curve for an idealised geothermal bore at incipient boiling for all points in the bore. These temperature profiles show no systematic change apart from the profile for M9, which shows general warming of about 5ºC since 1992. This would result in a water level change of about 0.1m(compared with the to 1m of water level change that has been observed from 1992 to 1998).

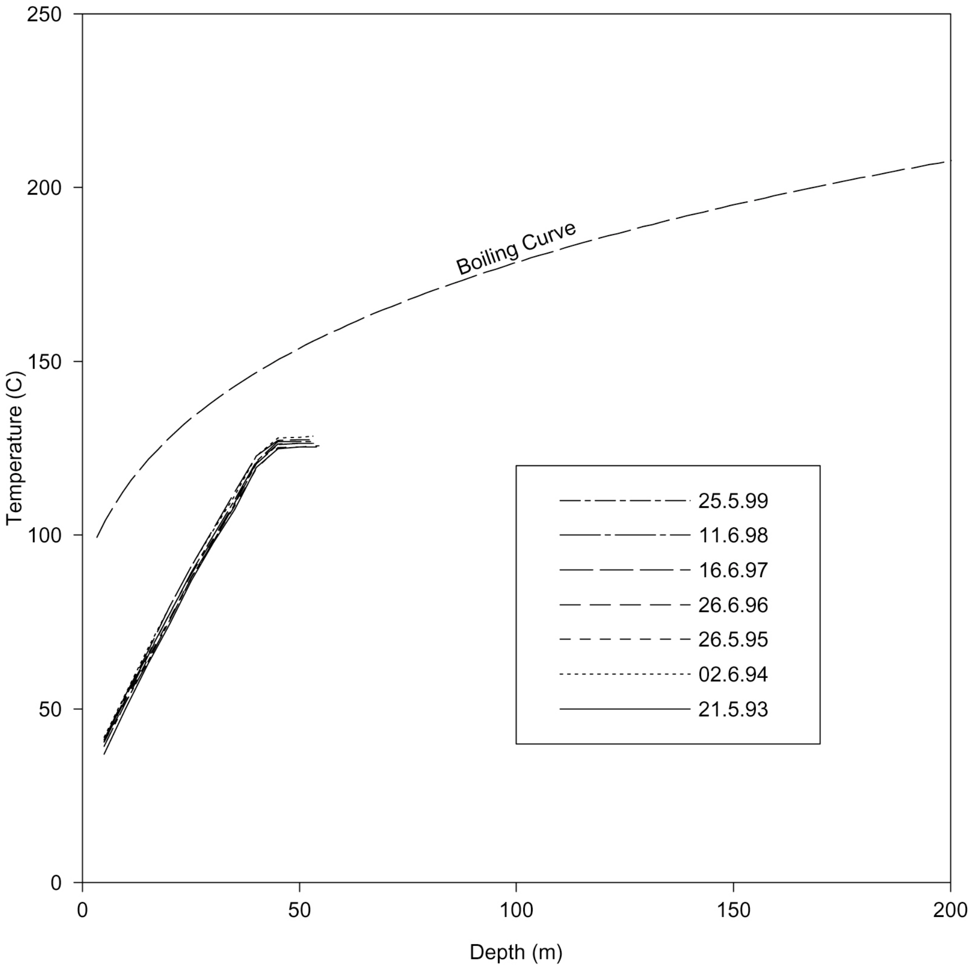


*Figure 5.14 Temperature profiles for M1.*

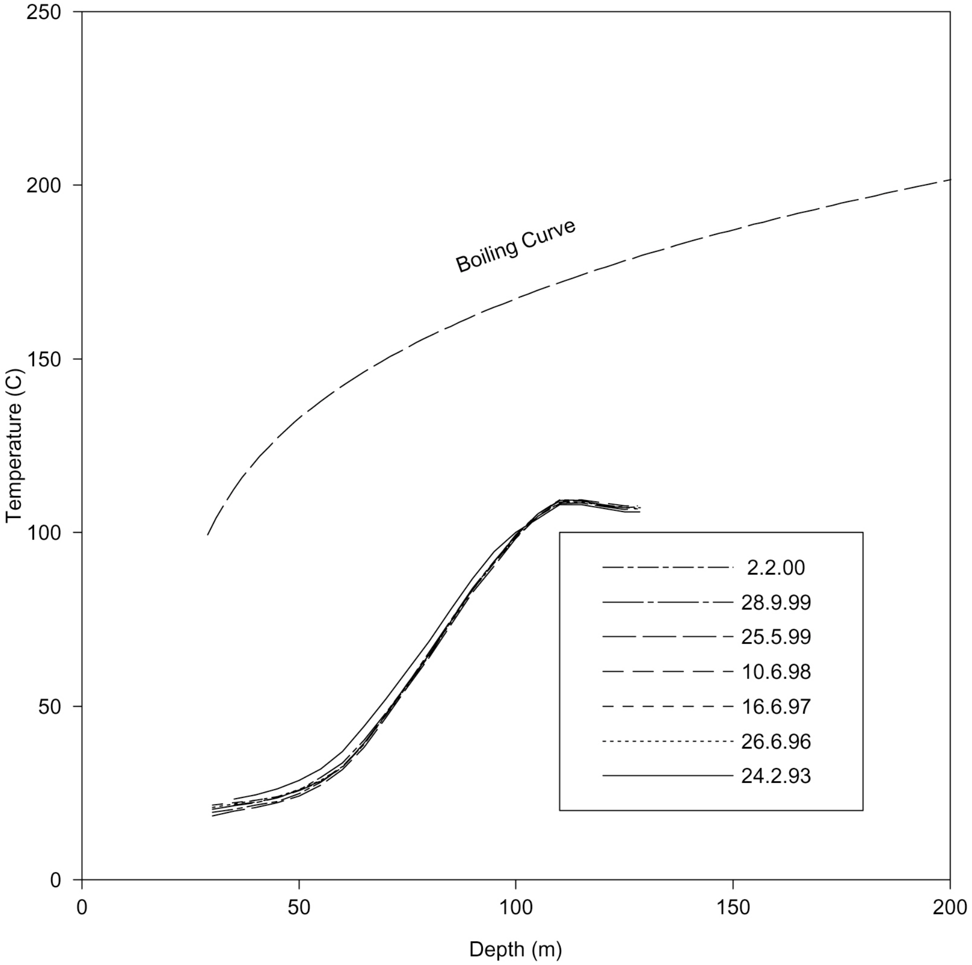


*Figure 5.15 Temperature profiles for M6.*

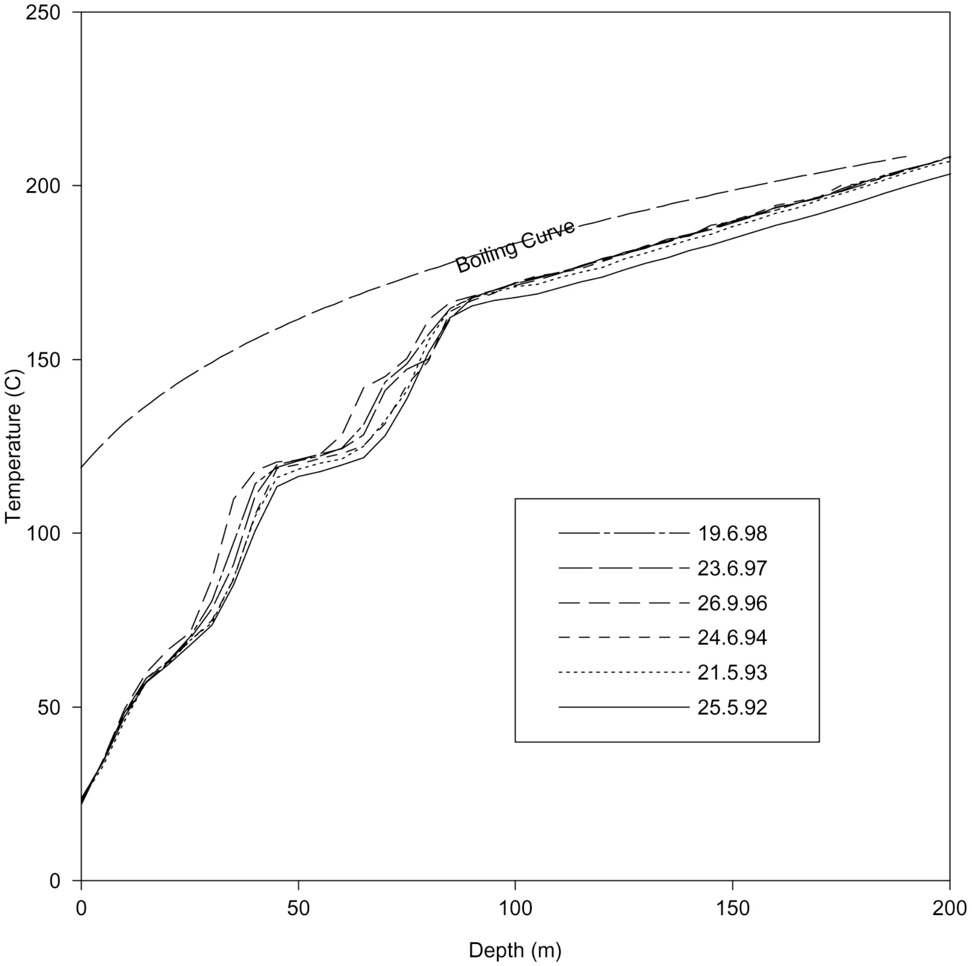


*Figure 5.16 Temperature profiles for M9 (from Kissling 2000).*

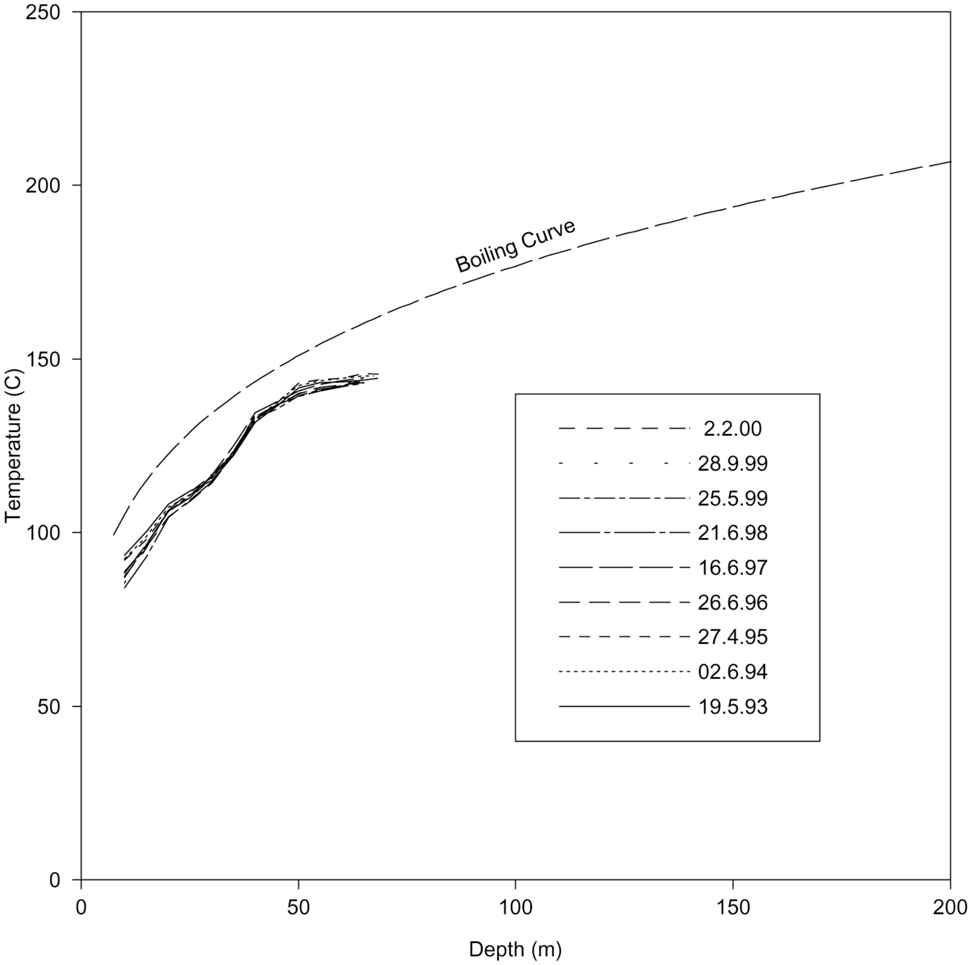


*Figure 5.17 Temperature profiles for M12 (from Kissling 2000)*

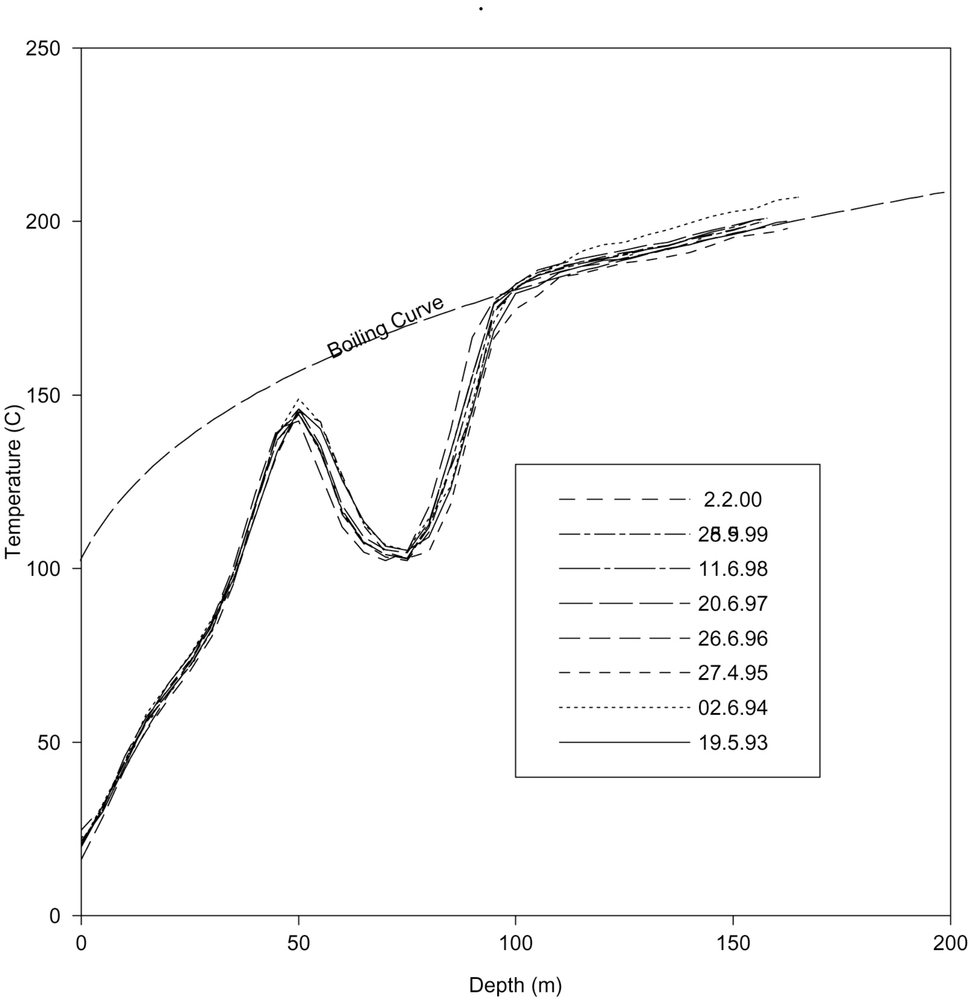


*Figure 5.18 Temperature profiles for M16 (from Kissling 2000).*

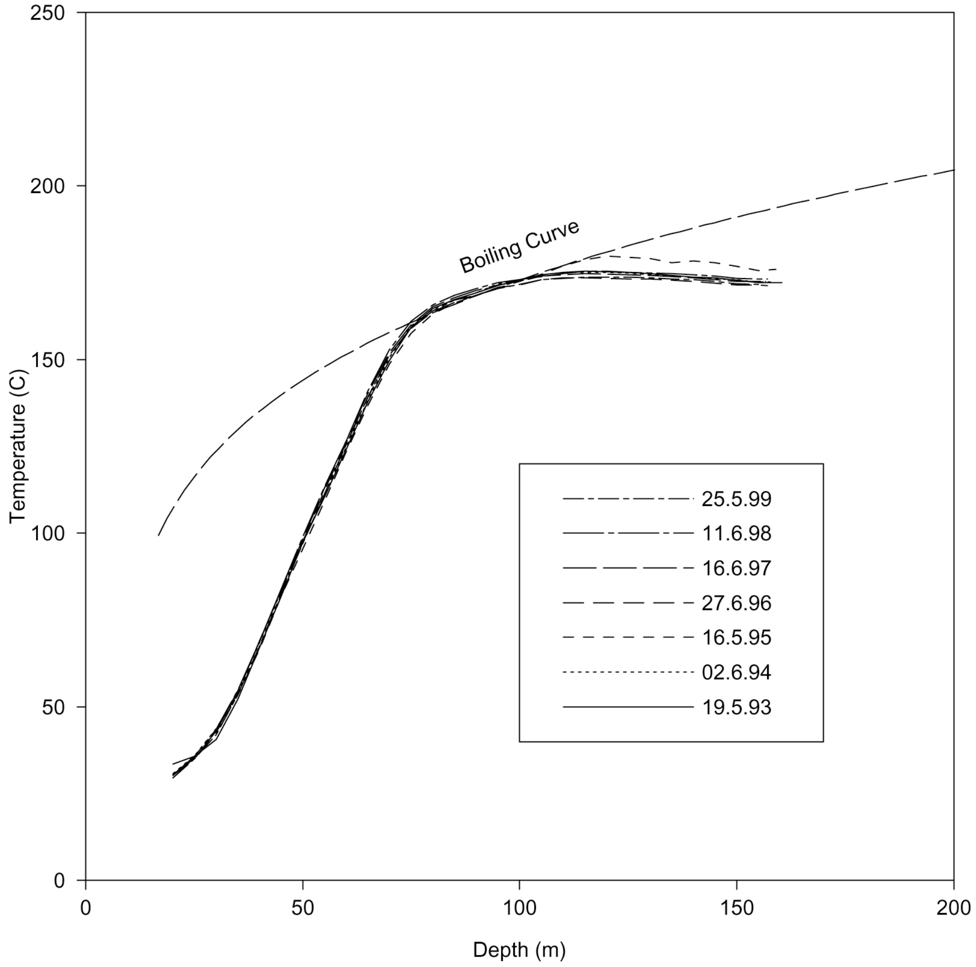


*Figure 5.19 Temperature profiles for M17 (from Kissling 2000)*

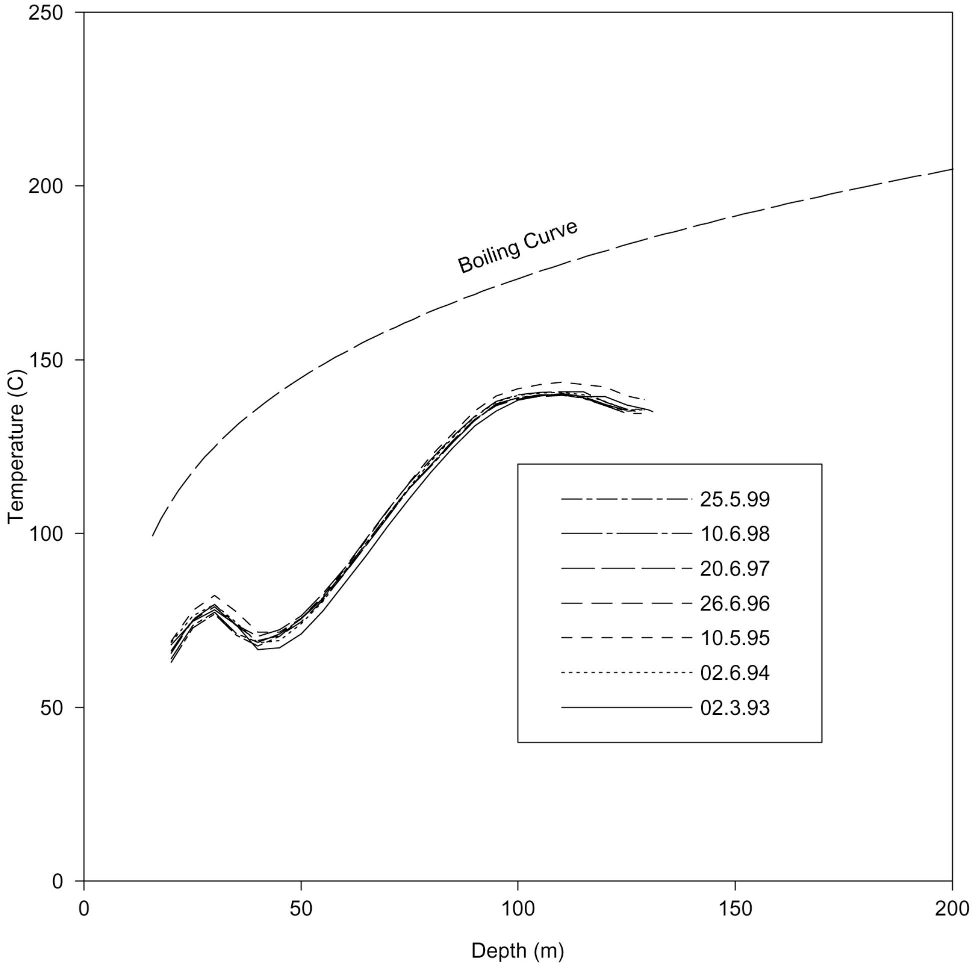


*Figure 5.20 Temperature profiles for M24 (from Kissling 2000).*

The temperature of the water column in a monitor bore affects the height of the column that is balanced by the pressure at the bottom of the column. The density of the water column is also affected by changes in the chemical composition of the column. The changes in composition can be assessed from data such as those in Glover and Heinz (1985). Over the period 1982 to 1985 when the composition was changing the fastest, the variation in composition generally did not exceed 15%. It is possible to asses the variation in density by assuming all the salts are present as NaCl and that the gases are present generally as the dissolved species $HCO_3^{=}$ and $HS^-$ and using partial molar volume data from Helgeson and Kirkham (1976). The variation in density due to the change in composition does not exceed 0.01%, so that changes in water level are extremely unlikely to have been caused by variations in composition. The variation in density due to temperature gives the change in height of the water column. Table 5.4 shows this rather small change for a 1ºC variation.

*Table 5.4 Variation in water level due to temperature changes compared with water level change during closure.*

| Bore No. | Water level change for 1ºC variation (m) | Water level change in closure period (m) |
|---|---|---|
| M1 | 0.03 | |
| M6 | 0.05 | 1.8 |
| M9 | 0.14 | 0.17b ≈ 1.7m |
| M12 | 0.05 | 0.8 |
| M16 | 0.13 | 2.0 |
| M17 | 0.16 | |
| M24 | 0.08 | |

The variations due to a 1ºC temperature error are only about 3 to 8% of the change during closure, and variation due to composition is less than one third of that. Measurement errors are likely to be random, so the long stable nature of most temperature profiles suggests they are reliable, and that water level acts as a good surrogate for pressure.

## 5.4 Ground Water Bores

Ground water bores penetrate a cold aquifer that overlies the geothermal aquifer, and contributes a component of pressure head to the geothermal aquifer. More importantly most waste geothermal water was discharged to shallow soakage pits. This resulted in a moderate component of both heat and mass contributing to the shallow groundwater from shallow soakage disposal. In some areas, such as the racecourse, there appears to be a leak of geothermal water into the ground water. As well as this, the comparison of the ground water level data (which responds very fast to rainfall), and the geothermal water level record, provided an insight to disturbances in the geothermal aquifer data that are likely to be due to rainfall (Figure 12).

Ground water levels and temperatures are recorded at approximately fortnightly intervals. Figures 5.21 to 5.25 give the historical records for water levels in the shallow ground water bores. These are taken from Kissling (2000). Figures 5.26 to 5.29 show the historical records for temperatures in the ground water bores, also taken from Kissling (2000).

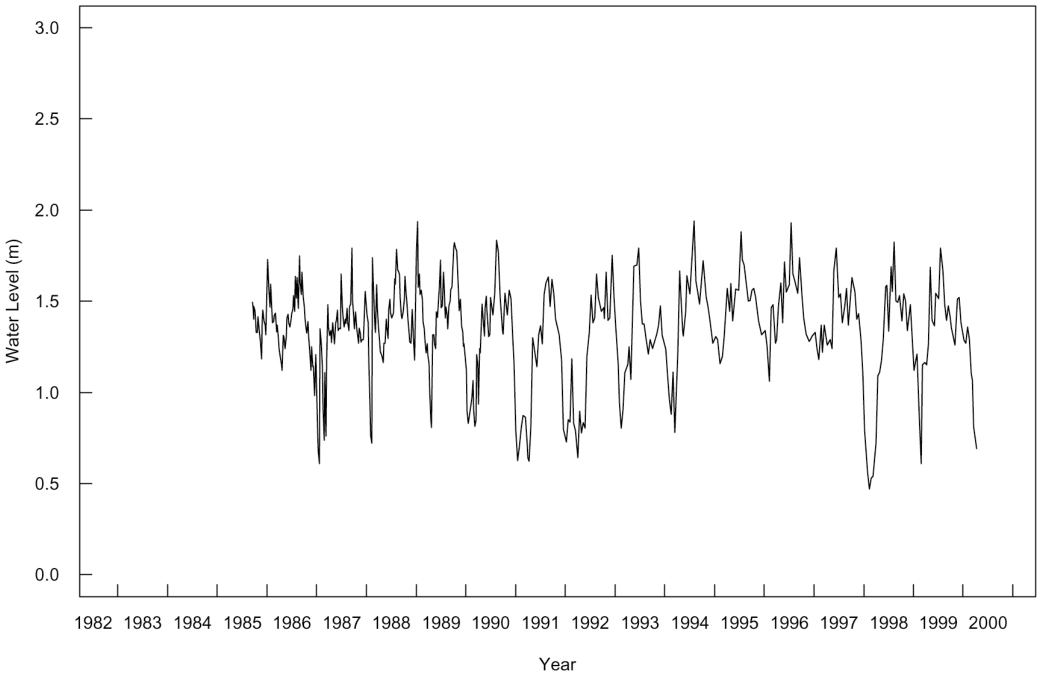


*Figure 5.21 Water level in Well G2 (from Kissling 2000).*

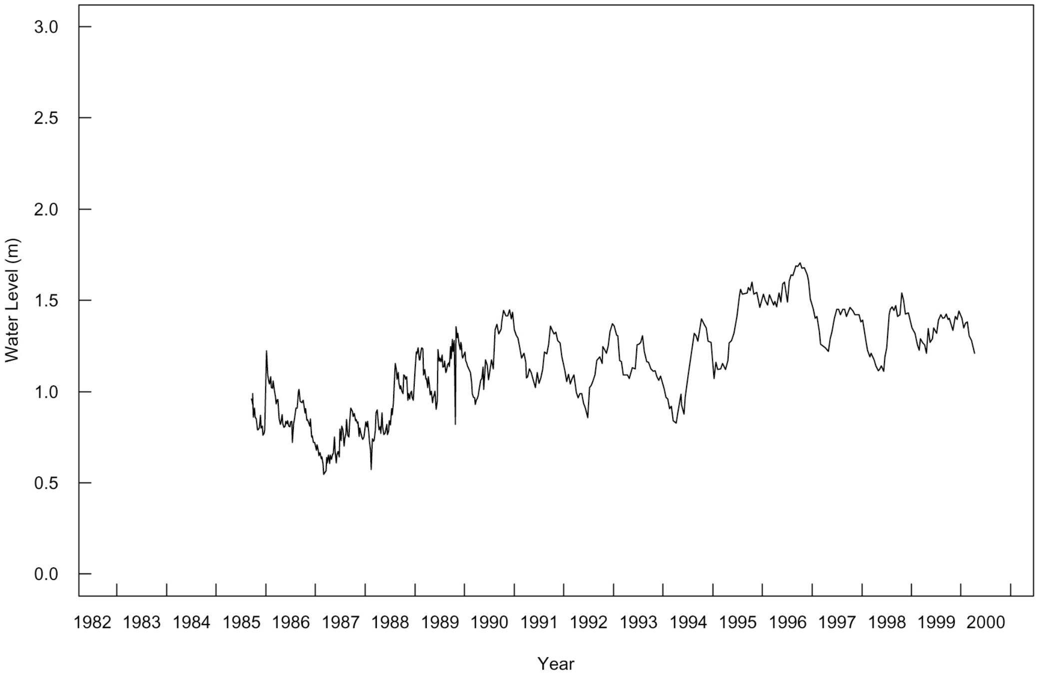


*Figure 5.22 Water level in Well G11 (from Kissling 2000).*

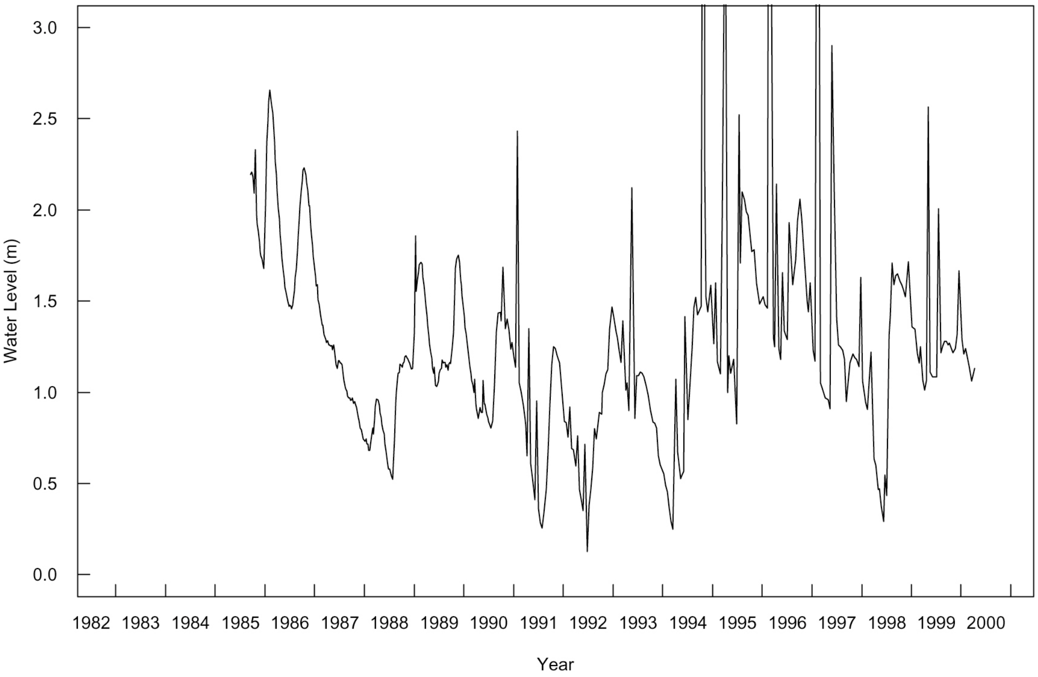


*Figure 5.23 Water level in Well G12 (from Kissling 2000).*

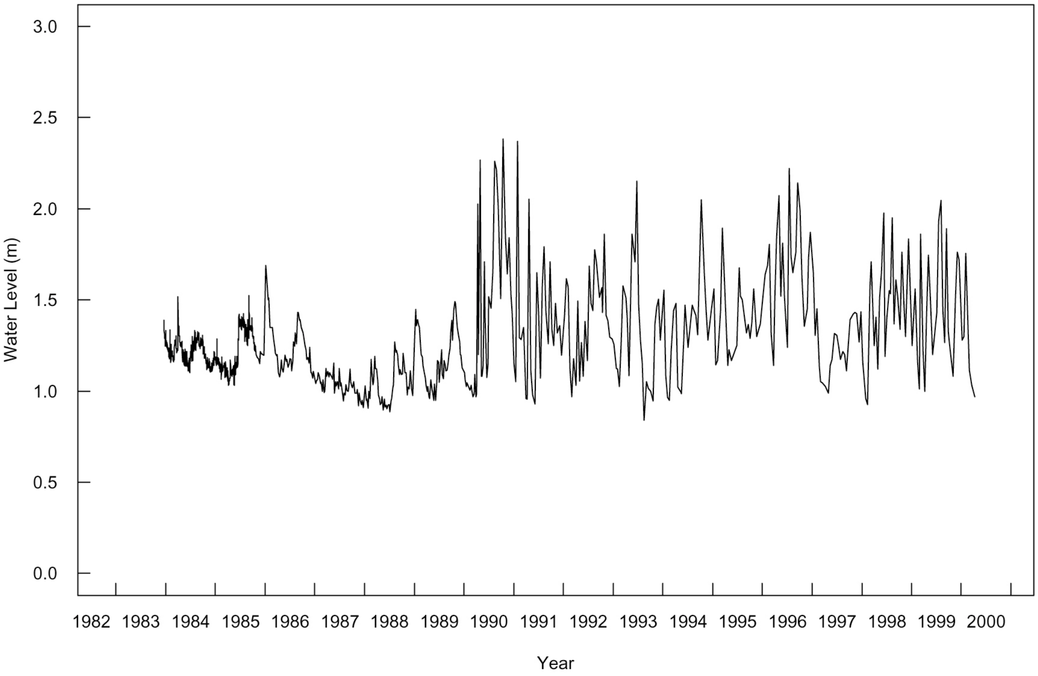


*Figure 5.24 Water level in Well G13 (from Kissling 2000).*

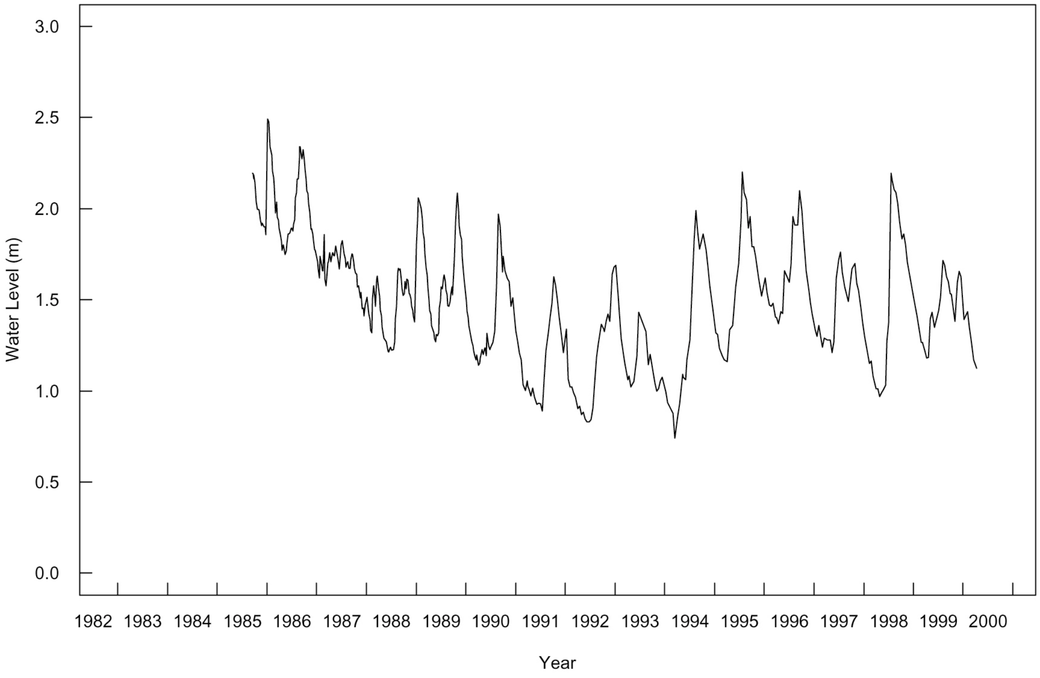


*Figure 5.25 Water level in Well G14 (from Kissling 2000).*

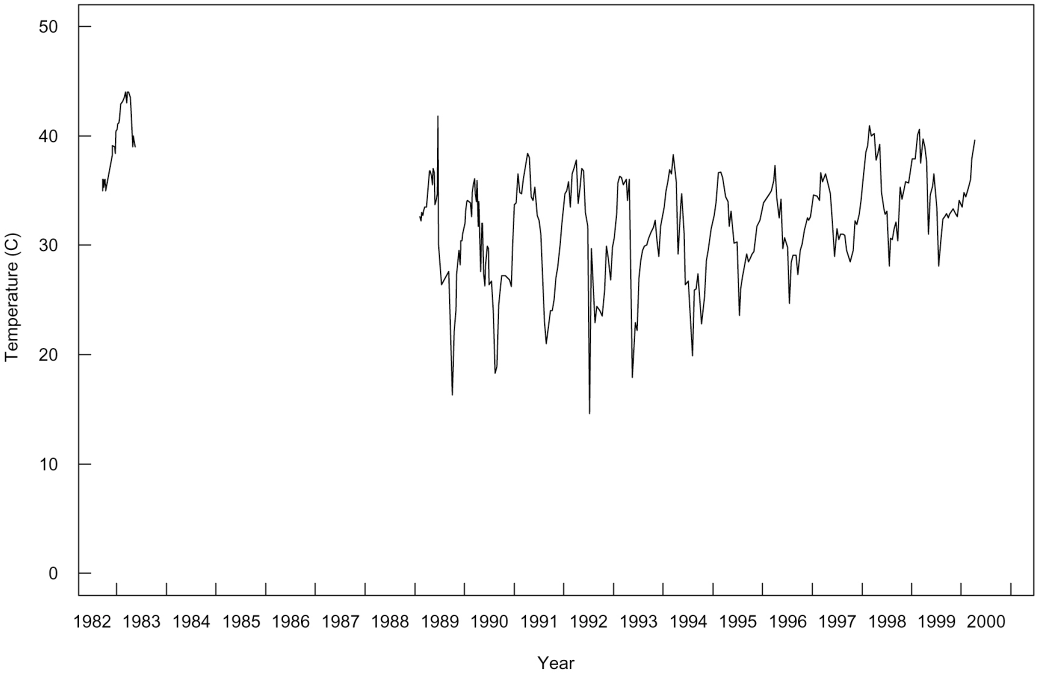


*Figure 5.26 Temperature in ground water Well G2 (from Kissling 2000).*

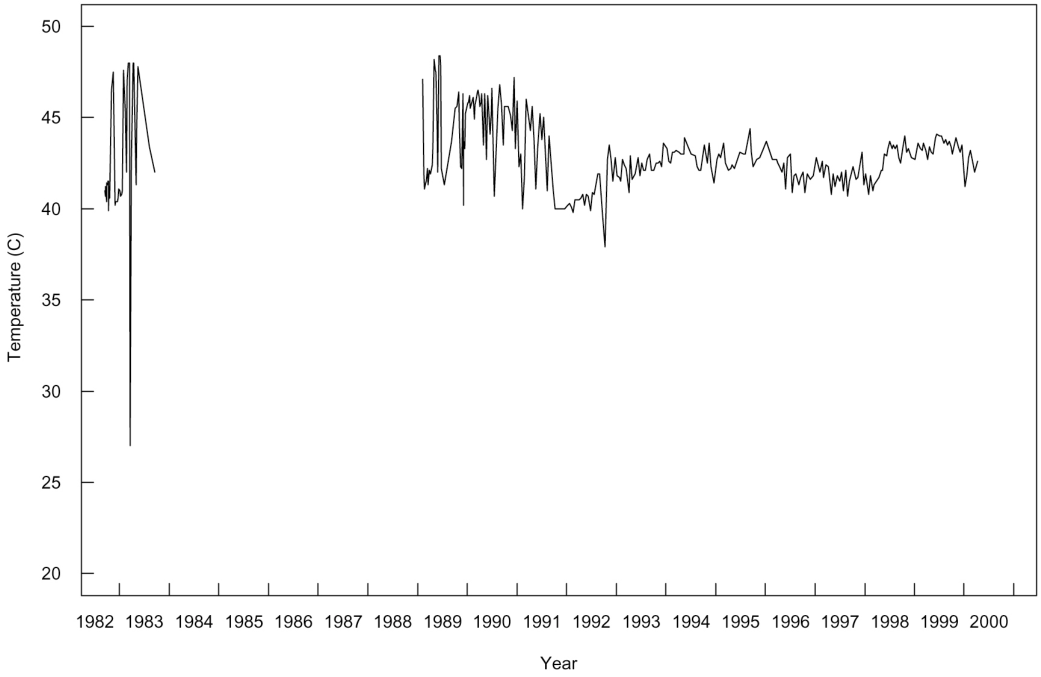


*Figure 5.27 Temperature in ground water Well G11 (from Kissling 2000).*

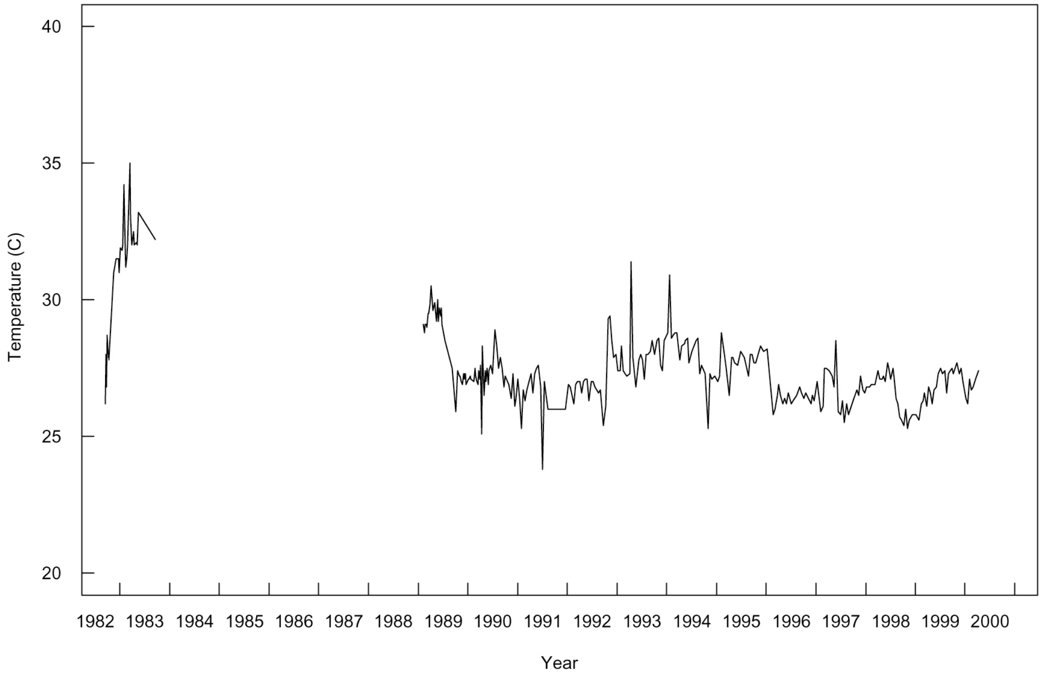


*Figure 5.28 Temperature in ground water Well G12 (from Kissling 2000).*

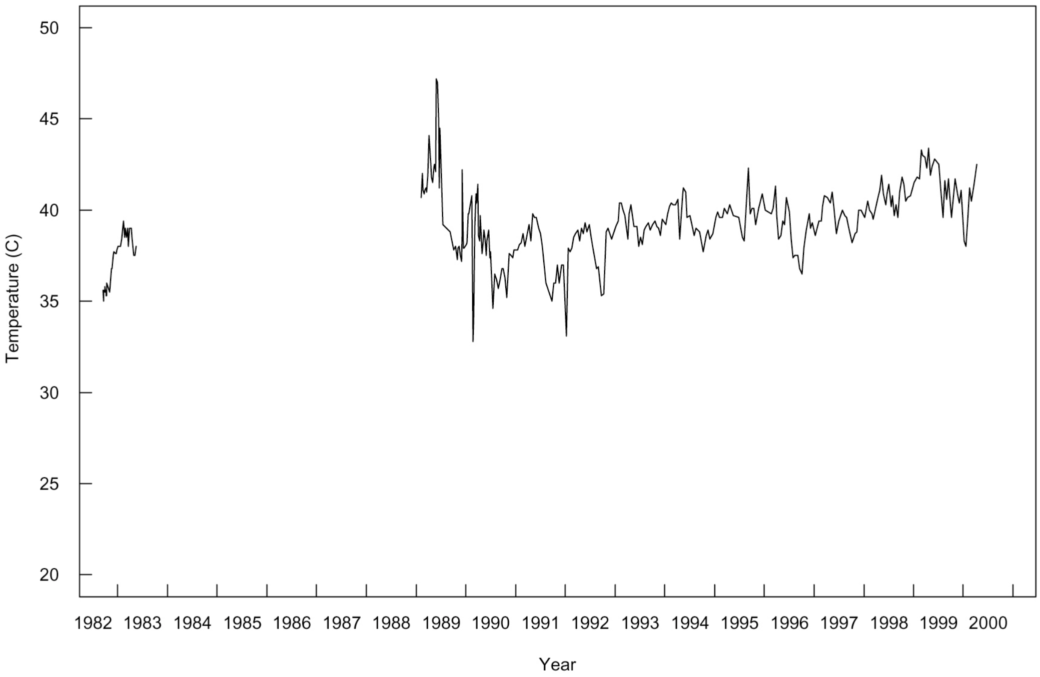


*Figure 5.29 Temperature in ground water Well G13 (from Kissling 2000).*

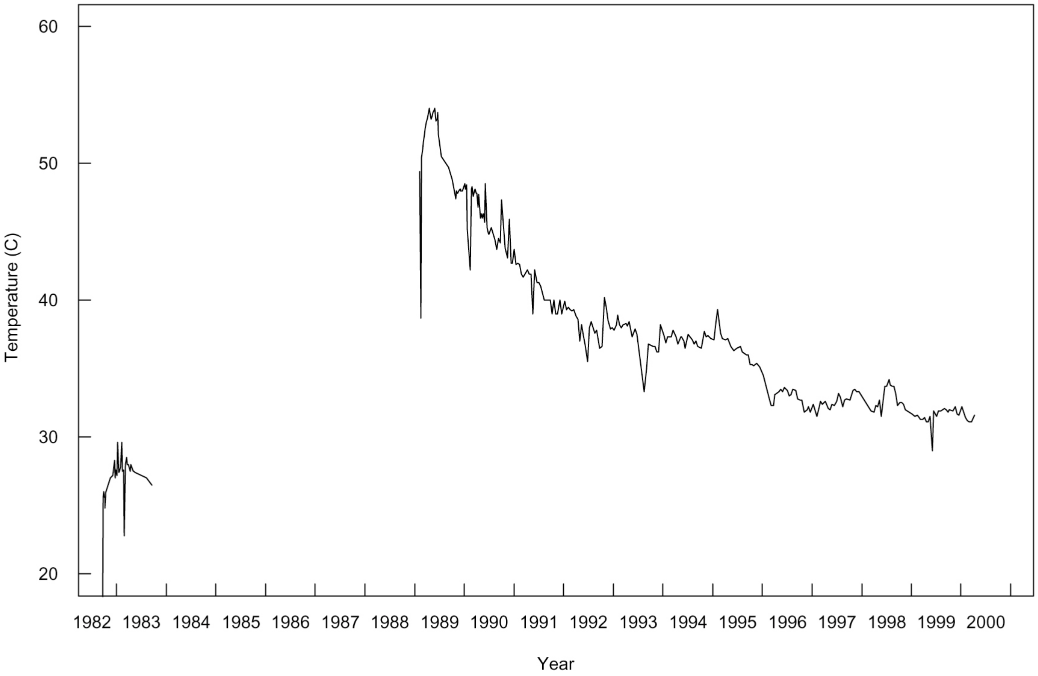


*Figure 5.30 Temperature in ground water Well G14 (from Kissling 2000).*

Continuous recording of water temperature data for most groundwater monitoring bores began in 1988, and just covers the end of the closure period. Earlier manual recordings of shallow groundwater level, (Burgess et al 1985) covers the closure period, and data for G13 (in the west) has a data cover the period from 1983.

### 5.4.1 Monitoring Bore G2

Monitoring bore G2 is located in the north in Kuirau Park and shows strong annual cycles in both level and temperature. The water level is probably strongly influenced by lake level. The annual variation in both level and temperature has been relatively constant until about 1990 or 1991, then decreasing slowly until 1997 when, abruptly, the summer level decreased and the temperature rose by nearly 5ºC. The annual pattern of temperature is now stable. It may be significant that this occurred at the same time as the first evidence of changes in Kuirau Pool and Tarewa Road.

### 5.4.2 Monitoring Bore G11

Monitoring bore G11 has shown a gentle rise in temperature across the period from 1987 to 1990 followed by a large annual variation, and an increasing average level. There was a high in the level record in 1996 followed by temperature fall in late 1990, to give a period of reduced variability in temperature with mean temperature falling slightly. This bore is near Roto-a-Tamaheke, but it appears that the level in the bore is not considered to be related to flow from Roto-a-Tamaheke.

### 5.4.3 Monitoring Bore G12

Monitoring bore G12 is located at the southern end of Fenton Street in Arikikapakapa Golf Course and exhibits a strong response to rainfall events. It has a variable annual cycle, and a yearly mean value which fell until 1993 but has risen slightly since then. Its mean annual temperature is stable.

### 5.4.4 Monitoring Bore G13

Monitor bore G13 is located near the Rotorua District Council sewage farm and has had a sustained period of high frequency high amplitude oscillations since 1990. Prior to this annual patterns were fairly constant, with the annual mean level falling until 1987 and annual mean temperature falling until 1990. Prior to 1990 G13 appeared to respond to rainfall events.

### 5.4.5 Monitoring Bore G14

Monitor bore G14 is located at the racecourse and shows large variations in level on an annual basis. Of all the groundwater monitor bores, G14 shows the most interesting water level and temperature changes. A shift from summer water level peaks in 1985/87 to winter peaks in 1994 onwards suggests a decrease in the input of waste geothermal water to the shallow groundwater. This is supported by the fall in temperature. A decline in water level of about 1m continued until 1994, but the water level has since been nearly constant.

A temperature peak of nearly 50ºC occurred in late 1988, which was followed by a temperature fall to around 35ºC in 1990. Chemical analysis suggests that the 1988 high temperature recorded in G14 was a steam heating episode. From 1990 to 2000 water temperature has been reasonably constant.

Comparison of the ground water level record with the geothermal monitor bore levels show that some of the rises in geothermal monitor bore levels are related to rainfall. The large rainfall events in 1983, 1986, 1988, 1989, 1990 and 1998 show up in the bore records as large peaks. They are particularly pronounced in geothermal monitor bore M12 (Figure 5.11), but even small rainfall events are apparent in the G series bores. The timescale for decay is also somewhat longer.

Water level in the groundwater aquifers also responds to water level in Lake Rotorua. The lake level has a static mean value with variations due to rainfall. Prior to 1990, lake level was included in the data collection. Variations in the level in G14 especially, and to a lesser extent other groundwater bores, correspond to variations in the lake level. The major characteristic of the level in the G series geothermal monitor bores is a short term level variation imposed on a varying mean value.

# Chapter 6: Natural Geothermal Feature Activity

## 6.1 Introduction

Natural geothermal features found across the field are the surface manifestations of geothermal activity or outflow from the field, and include:

- Geysers;
- Neutral to alkaline hot springs and pools;
- Fumaroles;
- Turbid acid pools and lakelets;
- Mud pools and mud cones;
- Barren warm or hot ground and solfatara;
- Dolines and craters (collapse and eruption).

Ever since early human occupation of the Rotorua area, natural surface features of the Rotorua Geothermal Field have been important resource to local Maori and later European peoples who settled here. The many hot springs of the field provided hot water for bathing and cooking and the surrounding warm ground making for comfortable living conditions, with many sites having great cultural significance.

In the late nineteenth century, visitors were attracted to Rotorua to see the unique geothermal sights that brought about settlement to support the growing tourism to the Rotorua area. Tourism is now a valuable economic activity for Rotorua city. It has been estimated that economic value is in the order of $310 million per year to the Rotorua District, with nearly 18% of all local employment either partially or totally dependent on tourism (Butcher, et al. 2000).

## 6.2 Natural Geothermal Features

Early scientific observations of geothermal activity were made by Skey (1878), who recorded approximate geographical positions and made descriptions and chemical analyses of springs and other natural features in the Rotorua area. More reliable mapping of features wasn't carried out until the 1890s, when maps for town planning purposes were produced.

Other studies that were undertaken later were: Grange, 1937, Marshall and Rands 1941, Crafer 1974 and Lloyd 1975. A very detailed survey of natural thermal features was carried out during the 1980's as part of the Task Force Rotorua Geothermal Monitoring Programme, (Cody and Simpson, 1985) but this was primarily focused on Whakarewarewa.

Environment B·O·P and Rotorua District Council recently undertook an inventory of geothermal features across the whole field to assist in better identifying potential risks and to aid in the protection of surface features. A comprehensive database of all known geothermal features (1511) and surface activity has now been compiled for the field (Cody, 2000).

The positions of all reported natural geothermal expression from the database generally fall in the 3 areas Whakarewarewa/Arikikapakapa to the south, Kuirau Park/Ohinemutu (on the shore of Lake Rotorua) to the north and Government Gardens/Ngapuna/Sulphur Bay to the north-east (also on the shore of Lake Rotorua) (Figure 6.1). There is very little transient geothermal expression outside these 3 areas.

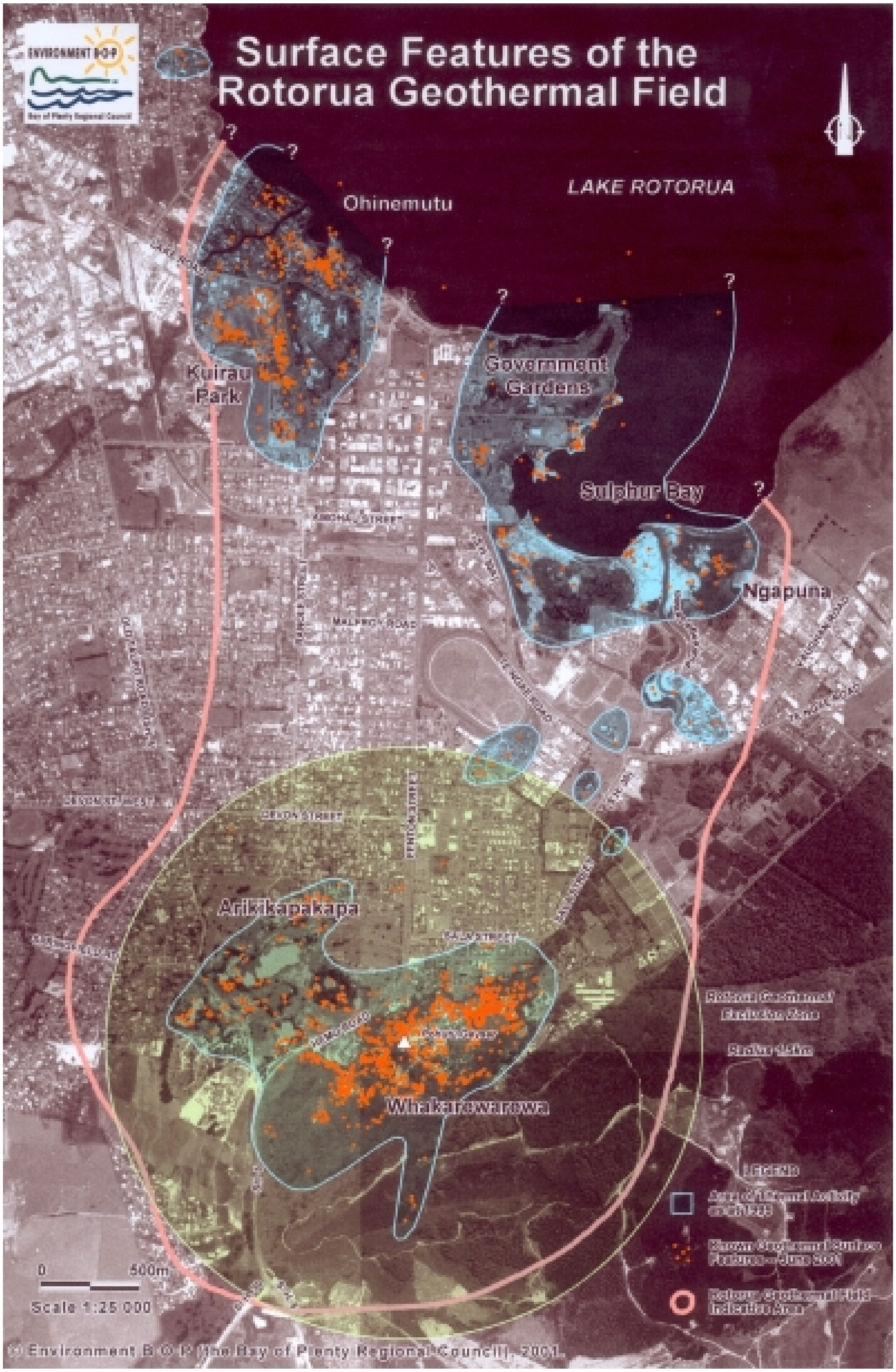


Figure 6.1 Reported positions of all reported natural geothermal features from the Environment B·O·P's natural geothermal features database. Features are grouped in the 3 areas Whakarewarewa /Arikikapakapa, Kuirau Park/Ohinemutu, Government Gardens/Ngapuna/Sulphur Bay).

Natural features can usually be grouped according to whether they are produced by: neutral to alkali-chloride geothermal fluid outflows (often saturated with silica); weaker upflows of alkali-chloride fluid mixing with groundwaters, or by gas and steam heating of ground waters or dry ground. These processes occur through the continuum of gas dominated to alkali-chloride dominated systems, with varying amounts of groundwater and air greatly influencing the surface forms. This is because of atmospheric oxidation of sulphides to produce strongly acidic conditions.

*Figure 6.2 An example of an alkali-chloride spring (Location: Whakarewarewa).*

Alkaline to neutral flowing springs (Figure 6.2) are most numerous at Ohinemutu and Kuirau Park in the north and at Whakarewarewa thermal valley in the south of the field. In this southern group, flowing alkaline clear springs only occur along the banks of the Puarenga Stream. A few occur on ground surrounding the shores of Sulphur Bay at Ngapuna and in Government Gardens.

Geysers are very rare and are now generally found at Whakarewarewa Thermal Valley. At brief intervals throughout historical time geysers have occurred at Ohinemutu and Kuirau Park but the underlying ground conditions appear to be too weak to contain boiling conditions for more that brief episodes and therefore the geyser activity that occurs at these locations is generally short lived.

The most common features are discoloured turbid, weakly acid ground waters that are often mixed with small amounts of deeper chloride geothermal water or steam/gas heated groundwaters or a mixture of the two. In the absence of surface water, mud cones or hot barren ground may form.

*Figure 6.3 An example of mud pool and mud cone surface features (Location: Arikikapakapa).*

Many examples of this type of activity are found at Arikikapakapa (Figure 6.3) and this type of activity can also be found in the three main thermal outflow areas of the Rotorua Geothermal Field.

## 6.3 Monitoring of Surface Features

Hochstetter, (1859) and later Malfroy (1891) made the earliest recorded observations of hot spring activity, but many of Malfroy's observations focussed on the artificial manipulation of features. During the 1890s to 1910s, caretakers residing at Whakarewarewa made detailed monthly written reports to the Tourist Department. These reports provided the exact eruptions times of Pohutu and other geysers, together with records of any other unusual thermal activity.

Although the early reports by Hochstetter (1859) and Malfroy (1891) and others were infrequent, they provide a useful description of the area some 100 years ago. Historical data shows little in the way of detail or analysis of geyser play activity, but there are indications from the 1890's that eruptions from Pohutu were so infrequent, that imminent eruptions could be signalled by raising a flag at the Grand Hotel (Braynart Group, 1979).

Grange (1937) produced detailed maps of thermal activity in Rotorua together with comprehensive accounts of spring and geyser activity during the 1920s and 1930s. In the 1940s, Marshall and Rands (1941) produced a report describing thermal activity in Rotorua along with detailed spring maps and some descriptions of water chemistry. Modriniak (1944) also visited Rotorua in response to the cessation of hot flows from the Roto-a-Tamaheke area and produced several unpublished reports and other potential supplies of hot water for public baths.

During the 1960's to the 1980's monitoring methods become more reliable and reporting much more consistent with accounts by Lloyd (1974, 1975). This work was aimed at cataloguing the resource rather than monitoring. During the 1980's a very intensive set of monitoring measurements were made by Cody and Simpson (1985) and Simpson (1985) which provided a benchmark to show when the field was under stress as a result of widespread bore use. Since then occasional monitoring has been used to record and identify changes in activity. Monitoring data that has been collected includes; discharge frequency and duration interval statistics of geysers; chemical changes; and fluctuations in activity. Mass discharge data is also used to quantify activity in the natural surface thermal features.

From 1998, Environment B·O·P has instigated monthly inspections and measurements of spring activity and characteristics in about 25 hot springs throughout the Rotorua Field. This work provides an ongoing database of thermal activity which assists Environment B·O·P to interpret and recognise trends in thermal activity.

Flowing hot springs (70-100°C) of near neutral to alkaline pH (6.7 to 9) with high chloride (300-1500 ppm) and low sulphate (10-80 ppm) contents are preferred spring types for monitoring purposes because fluid discharged from these springs is more similar to the deep geothermal fluids found in production bores. These near neutral to alkaline springs are good indicators of natural geothermal outflows from the field.

Many springs and geysers have up to 150 years of intermittent records of information but only a limited number of springs and geysers have substantial quantitative observations and measurements spanning many decades, which can be used for assessing trends or changes in activity. The discussion below is limited to features with a relatively adequate record of activity.

## 6.4 Southern Springs and Geysers

In the southern areas of the field, natural geothermal activity is concentrated in the Whakarewarewa thermal Valley and the Arikikapakapa Reserve. Geysers and flowing boiling alkaline hot springs, acid springs, mud cones and mudpools, turbid acidic pools and solfatara all occur in Whakarewarewa. To the northwest is the Arikikapakapa Reserve, which contains numerous cool turbid acidic laklets, boiling mud pools and barren solfatara. This area is underlain by a boiling zone so that its surface features are a product of gas and steam alteration and interactions with surface groundwaters (Cody and Scott, 2000). However a significant chloride outflow also occurs within Arikikapakapa Lake indicating that some deep geothermal up flows are present. Further to the west near the shores of a small lake (Tangaturua) old sinter deposits confirm the existence of prehistoric overflowing alkaline springs in the area (Scott and Cody, 2000).

### 6.4.1 Whakarewarewa Thermal Valley and Geyser Flat

At least 65 geyser vents are recognisable through Whakarewarewa Valley today, although it is unlikely that more than a handful of these have been active at any one time. Natural changes are continually occurring to geyser and springs as a result of: silica deposition changing the dimensions of conduits and channels; rupturing of flow channels; and total closure of conduits. For example on geyser flat fractures across the sinter terraces were found on 16 August 1984, 18 October 1988, 7 December 1989 (when pyritised ejecta was erupted out of Prince of Wales Feathers geyser), 27 March 1991 and again on 16 May 1991. The fracturing on 18 October 1988 created a new geyser, about 3m north of Prince of Wales Feathers. This new geyser played 2-3 m high until early 1999. These fractures appear to be associated with movement of the Te Puia Fault (Scott and Cody 2000). These types of natural changes compound the problems with interpreting geyser changes through time.

Since the 1950's nine geysers have been active at the Whakarewarewa thermal area (Figure 6.4), and of these, six have been active in the 1990's. Seven of the geysers are intimately connected over the north-south lineation of the Te Puia Fault (Lloyd 1975). Lloyd (1975) showed the existence of shallow and rapid (less than 24 hrs) connections between all these geysers with a series of dye tracings experiments during the 1950s-60s. As a consequence of this interconnection between the geysers, it is not possible to make reliable predictions of impending eruptions for any individual geyser, although overall patterns of activity have been recognised.

Using qualitative data from the 1890's-1920's and instrumental recordings from the 1950s onwards, records of geyser activity have been compiled that presents a clear trend of declines in outflows and failing geysers during the 1950's-80's (Figure 6.5). For example Waikite geyser ceased erupting in April 1967; Papakura geyser ceased all eruptions in March 1979; Te Horu ceased all geysering by 1972 and Korotiotio ceased surface overflows in late 1979 (Cody and Lumb, 1992). However since 1987 there has been significant recovery of spring flow and geyser eruption activity. From 1992 there has been further resumption of spring flow and geyser activity with Pareia geyser, at the southern end of Waikite Mound, resuming frequent geyser eruptions in late 1988; in 1995 Parekohoru (Champagne Pool) recommenced boiling surges and overflowing and in January 2000, Te Horu geyser has resumed hot overflows (Scott and Cody 2000) (Figure 6.5).

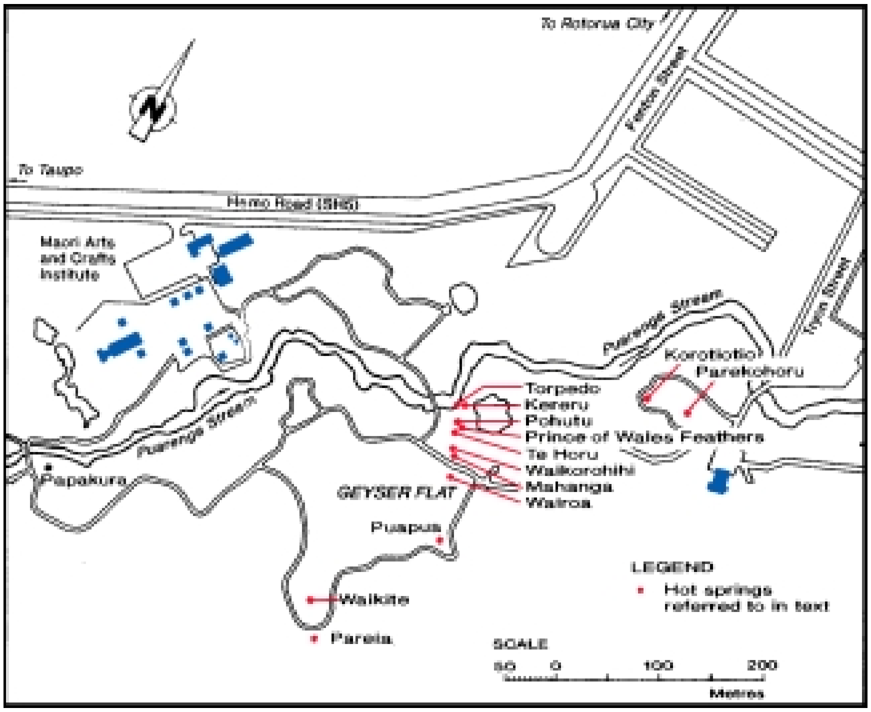


*Figure 6.4 Location of major springs and geysers at Geyser Flat – Whakarewarewa thermal area.*

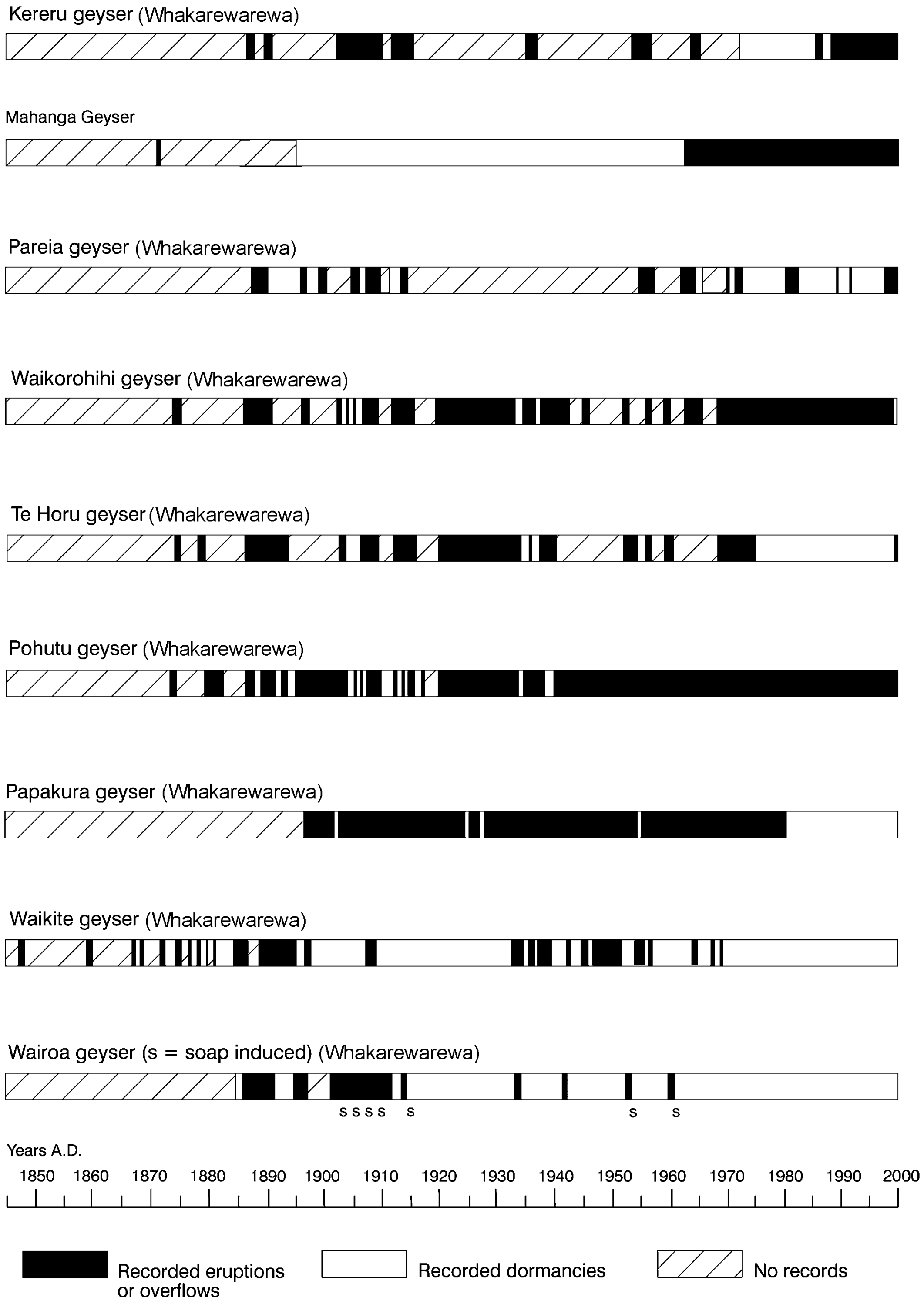


*Figure 6.5* *Histograms of known activity of geysers at Geyser Flat – Whakarewarewa through time. Papakura, Waikite and Wairoa have been dormant since the 1970's.*

### 6.4.2 Pohutu Geyser

Pohutu is the largest most widely known of all the geysers that are presently active at the Whakarewarewa thermal area and is an icon for tourism to the Rotorua and New Zealand. Pohutu is also significant in that it was used as the centre point of the 1.5 km bore closure zone in 1986 (Cody and Lumb, 1992). Pohutu typically erupts 10-60 times a day and historically averaging 10-30 percent of a day in eruption with a "typical" full column eruption height of about 21m (Scott and Cody 2000).

The pattern of activity from Pohutu Geyser continues to change through time (Figure 6.5). From earliest records in 1845 up until the 10 June 1886 volcanic eruption of Mount Tarawera, Pohutu seldom erupted at all and was very erratic, with sometimes many weeks or months between eruptions. After the June 1886 Tarawera eruption, Pohutu Geyser activity was monitored more frequently. Natural increases in its play frequency occurred during 1886 to 1891 but the Resident Town Board Engineer experimented with controlling and stimulating geyser eruptions by manipulating the surface water flows (Malfroy, 1891). This meant that the eruption frequency of Pohutu during the 1890's was possibly due more to human activity rather than natural processes.

From 1900's until the 1930's Pohutu had very irregular eruptive activity but usually erupted on average 5-8 percent of the day, although periods of many days and weeks without eruptions were common (Figure 6.5). Eruption activity from 1900 to 1920 characteristically may have been infrequent but a much larger percentage of eruptions lasted over an hour (Cody and Lumb 1992). After the 1920's the distribution of eruption duration shifted to a pattern of eruptions lasting 15-30 minutes, with few lasting less than 5 minutes. This pattern remained until the 1970's when Pohutu showed a pronounced shift to more frequent but shorter duration eruptions but with an increased number of eruptions per day. This was a shift from 5-13 % of the day in eruption during 1900 to 1960 to over 30 % of the day in eruption by 1970's (Figure 6.6).

By July 1986 about 17 percent of all eruptions were less than 5 minutes duration with almost half lasting less than 10 minutes (Cody and Lumb 1992). Eruptions would degenerate into a continuously steaming phase, with droplets of water and no overflows (Cody 1986b).

From 1988 Pohutu resumed longer full column eruptions, although these were typically only a few minutes duration. From a small sample of eruptions in 1989, almost 10 percent were more than one hour's duration compared to 2 percent in 1986 (Figure 6.7; Cody and Lumb 1992). Sampling of eruptions from 1996-98 showed Pohutu had changed to numerous short duration eruptions of 2-5 minutes occurring up to 60 or 80 times per 24-hour day (30 percent of day in eruption; Figure 6.8). By 1999 some of these short duration eruptions began to blend into longer plays and from 17 March 2000 until 17 April 2001 (over 365 days) Pohutu played continuously, mostly as a full column approximately 20m high. During April and May 2001 Pohutu geyser rarely had any full column eruptions at all, with a few lasting only a minute or less. From the start of June 2001 it resumed longer and more frequent full column eruptions, with 5-10 minute duration eruptions and complete dormancies between eruptions. This pattern of activity is similar to that which occurred in 1997-1998.

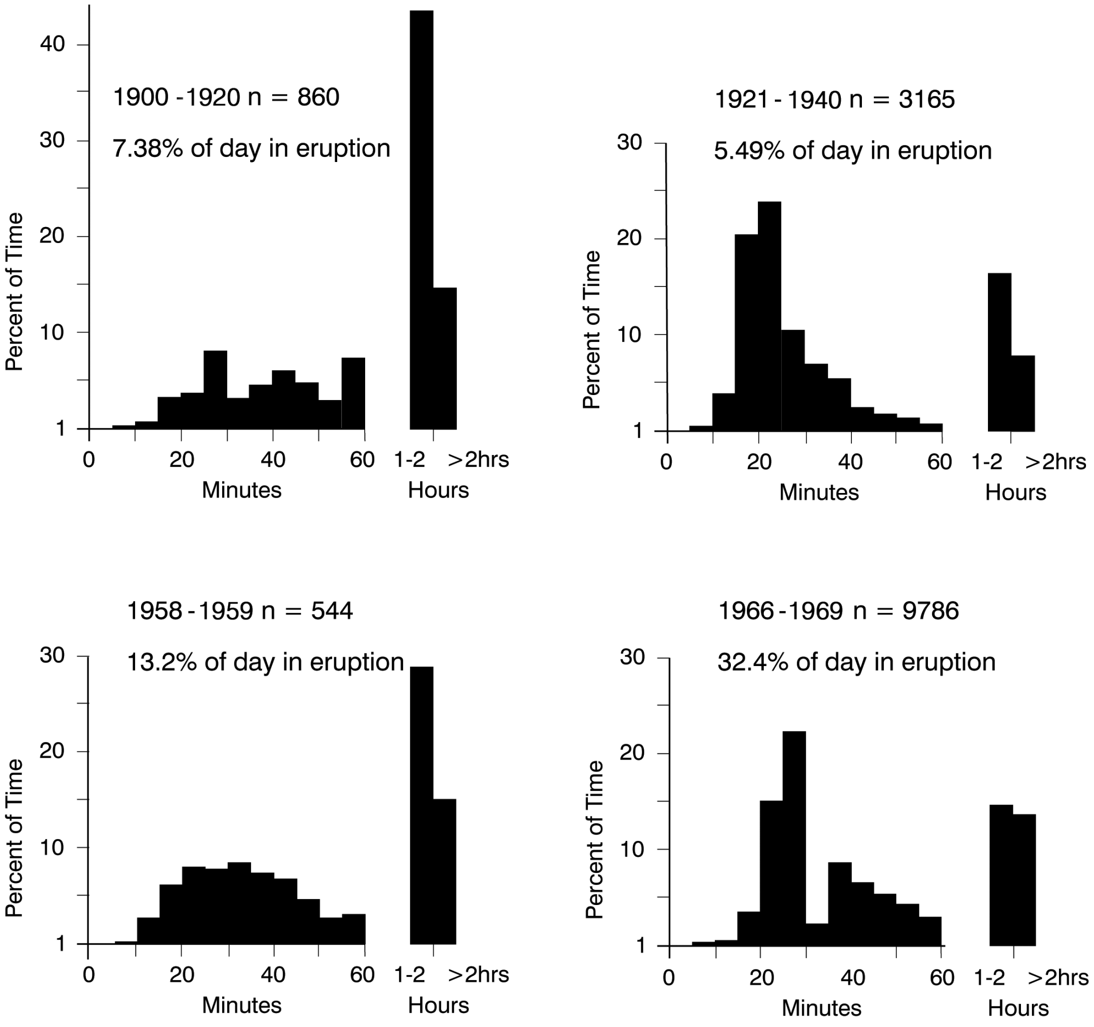


*Figure 6.6* *Histogram plots of Pohutu geyser eruptions durations for 1900-1920, 1921-1940, at times of pre-bore exploitation, 1958-1959 and 1966-1969 at times of early exploitation of the field. Eruptions are grouped into five minute intervals up to 1 hour duration, then 1-2 hours and > 2 hours. All eruptions are shown as a percentage of the total recorded. Note that the number 'n' is the number of eruptions plotted for each histogram plot and not the total of all eruptions that occurred for the time period(years) sampled.*

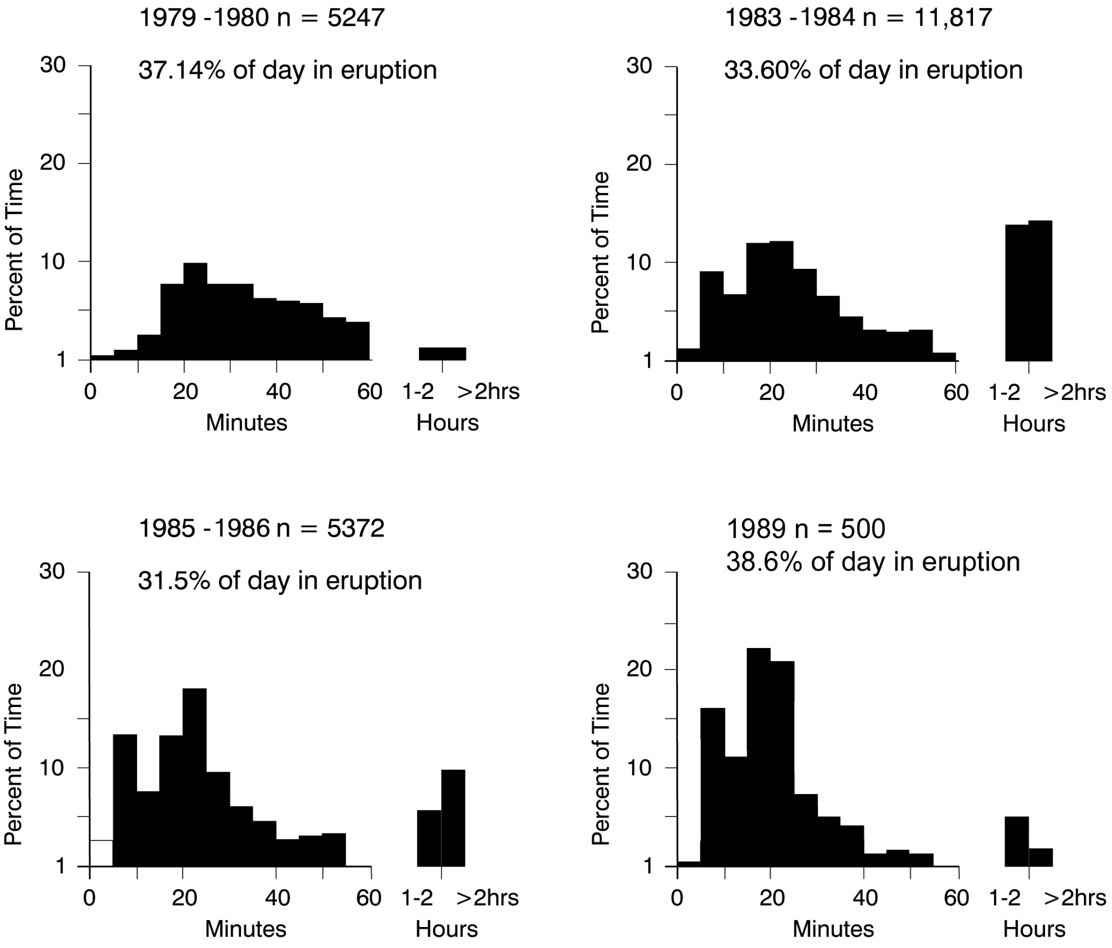


*Figure 6.7* *Histogram plots of Pohutu geyser eruptions durations for 1979-1980, 1983-1983, 1985-1986 at times of intensive exploitation of the field. Eruptions are grouped into five minute intervals up to 1 hour duration, then 1-2 hours and > 2 hours. All eruptions are shown as a percentage of the total recorded. . Note that the number 'n' is the number of eruptions plotted for each histogram plot and not the total of all eruptions that occurred for the time period(years) sampled.*

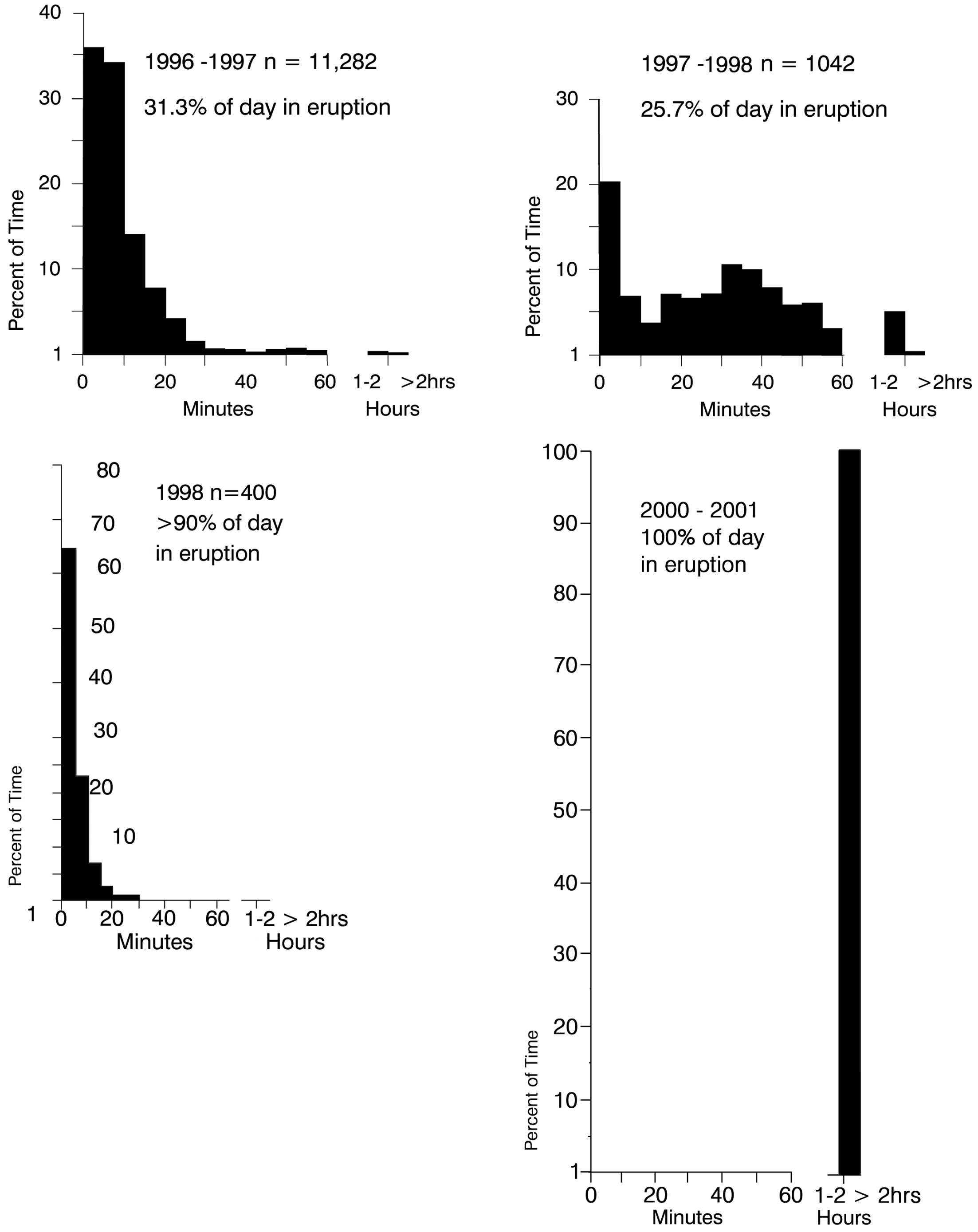


Figure 6.8 *Histogram plots of Pohutu geyser eruptions durations 1989, at times of bore closure and post closure field recovery phase, 1996-1997, 1997-98, 1998, 2000-2001 at times of field equilibrium and surface feature recovery. Eruptions are grouped into five minute intervals up to 1 hour duration, then 1-2 hours and > 2 hours. All eruptions are shown as a percentage of the total recorded. Note that the number 'n' is the number of eruptions plotted for each histogram plot and not the total of all eruptions that occurred for the time period(years) sampled.*

### 6.4.3 Prince of Wales Feathers Geysers

Prince of Wales Feathers geyser was formed after the 10 June 1886 eruption of Mount Tarawera. It is located 2.5 m north of Pohutu geyser at the edge of a prominent sinter mound enclosing both Prince of Wales Feathers and Pohutu (Figure 6.4). It has always played about 8-12m high during its strongest eruption phase, with a weaker splashing play of 1-3m high being its most common play style. From 1886-1901, it was known by guides and caretakers simply as "The Indicator" as it commenced geyser activity several hours before Pohutu geyser erupted.

Throughout the twentieth century Prince of Wales Feathers geyser continued to commence eruptions just before Pohutu and Waikorohihi geysers began their eruptions. It would strengthen its eruption by playing higher and more steadily within a few minutes of Pohutu and Waikorohihi geysers beginning their own eruptions. During the 1950's-1970's it erupted about 25-35% of each 24 hr day and invariably played throughout each eruption of Pohutu geyser.

During 1992 Prince of Wales Feathers changed to almost continuous eruptions lasting greater than 95% of each day. Increased outflows of hot water killed off surrounding algal growths and silica was deposited over an area of about $150m^2$ around the geyser. It has also played nearly continuously through March 2000 to April 2001 while Pohutu was in constant eruption. Since April 2001 Prince of Wales Feathers has developed discrete eruption cycles, with long dormancies generally accompanying those of Pohutu.

### 6.4.4 Te Horu Geyser

Te Horu is a large (about 5 m diameter) open vent immediately south of Pohutu and is likely to be interconnected to Pohutu and Waikorohihi geysers (Figure 6.4; Cody and Lumb, 1992). Te Horu erupted 10-15 times per day to approximately 5-7m high with large overflows until about 1972. From 1987 the water level in its vent had fallen several metres below over flow and no true geyser activity (Figure 6.5) was seen from Te Horu during the 1980's when the water level in the vent remained below overflow (Bradford et al., 1987).

In the late 1990's the water level in Te Horu began rising progressively and in January 2000 it resumed overflow from the vent but this has always been below boiling (approximately $76^oC$) and coincident with eruptions from Pohutu. It now appears that Te Horu is receiving discharge waters from Pohutu geyser.

### 6.4.5 Mahanga (Boxing Glove) Geyser

Mahanga geyser is also known as Boxing Glove, in allusion to the shape of its enclosing sinter mounds. It is located approximately 20m south of Pohutu and 4m south of Waikorohihi geyser (Figure 6.4). The eruption activity from Mahanga geyser is unusual because there is no record of activity until October 1961 (Lloyd, 1975).

Records of Mahanga geyser activity from the 1980's indicated eruptions occurred for 20-23% of each 24-hour day. Eruptions usually lasted for 13-20 seconds every 60-80 seconds and typically were 3-5m high with weak overflows of less than 1 ℓ/s. Mahanga Geyser eruptions would often become shorter and further apart whenever

Pohutu or Waikorohihi were erupting, at which time Mahanga could occasionally “miss” an eruption, or erupt 1-2m high with no overflows.

In 1999 Mahanga geyser eruptions were still regular but since then geyser activity has progressively decreased and eruptions have become erratic. During 1999-2000 several days would sometimes pass without eruptions and by 2001 eruptions had become rare usually with days or weeks of inactivity.

### 6.4.6 Waikorohihi Geyser

Waikorohihi geyser is located about 20m south of Pohuhtu geyser and 3m north of Mahanga Geyser. It has been active throughout historical times (Cody and Simpson, 1985; Cody and Lumb, 1992) and has also been observed to have unusually high (about 13m) sporadic eruptions and dormant periods up to weeks at a time. In the 1960’s and 1970’s Waikorohihi typically played 12-20 times per day, with long periods (25-40 minutes) of overflow.

During the 1980’s instrumental recordings showed Waikorohihi typically erupted for 55-65% of the day with 12-15 eruptions per day. Typically these eruptions were 5-8m high with overflows of 5-10 ℓ/s, but in 1986 the eruption style changed to long dormancies of 20-35 hours, compared to 1 hour which was previously considered “normal’ (Cody Lumb 1992). During the 1990’s eruption activity from Waikorohihi decreased, with fewer eruptions and of shorter duration. During 2000 no eruptions were observed when Pohutu was continuously erupting.

### 6.4.7 Kereru and Wairoa Geysers

Kereru geyser is at the northern base of Geyser Flat on a lower sinter terrace alongside the Puarenga Stream (Figure 6.4). In the late 1800’s and up until the 1920’s, Kereru had irregular large eruptions that were weeks or months apart and were generally very short lived (typically only 15-25 seconds duration) but 7-20m high with large overflows flooding over the lower sinter terraces. Between geyser eruptions, Kereru was typically continuously boiling and splashing with sporadic weak overflows.

From about 1972 until January 1988 no natural eruptions were ever observed (Figure 6.5), however a few soap induced eruptions were made for photographic purposes. This period of dormancy coincided with the general decrease of spring and geyser activity elsewhere at Whakarewarewa. However, eruptions of Kereru have no apparent relationship to any other geyser activity. A possible explanation may be its different water chemistry from the rest of Geyser Flat vents. Kereru consistently has about 20% less chloride than other geysers and its tritium isotope results indicate that it is the only geyser with fresh water inputs.

From 1988 to 2000 Kereru was rarely seen in eruption but usually boiled continuously with splashes 1-3m high and weak overflows. On one occasion it was observed to erupt up to seven times in one daylight period of less than 9 hours.

Wairoa geyser is about 15m south of Mahanga geyser and is also on the Te Puia Fault. It has not erupted naturally since 10th December 1940 although many large (40-50m high) soap induced eruptions occurred during 1958-59 (RMP, 11/12/40) (Figure 6.3). By 1981 the water level was 4.5m below overflow and had become an acidic (high sulphate - low chloride) continuously boiling pool. In 1996 the water level rose in the vent to about 3.2m below overflow and remains so at the time of writing.

## 6.5 Other Whakarewarewa Geysers and Hot Springs

During recent decades several episodes of sporadic and brief geysering have occurred from other known geysers. At the eastern end of Roto-a-Tamaheke (Figure 6.9) spring S435 geysered many times daily to 3-5m high in March-April 1983, but its vent was physically damaged by human intervention and it has not geysered since (Figure 6.10).

Okianga geyser (spring S488; Figure 6.9) played approximately 4m high every 35-60 minutes of the day throughout most of the late 1980s to the late 1990's (Luketina, 1996; Cody, 1998). In the early 1980s it rarely erupted but of the eruptions that did occur these correlated to high or low air pressure changes. By 1999 the ground surrounding it had opened several small fissures which have developed new boiling flowing vents but geysering activity from Okianga has now ceased.

### 6.5.1 Waikite Geyser

Waikite is on top of a prominent sinter dome at 315m asl (Figure 6.4). In the past eruptions have always been very erratic and it last erupted in 1967 (Figure 6.5). During the 1980s its vent was always blocked with sinter rubble and constantly steaming. In the early 1990s a collapse of the sinter blockage opened the vent once more, which can now be sounded with a leadline to 8m depth onto a rocky floor.

The vent has filled to within 3.2-3.5m of overflow with clear constantly boiling waters several times in the 1990's. Each time the water has been less than 5ppm chloride and very high sulphate, indicating it is only steam and gas heated fresh water, not deep geothermal water.

### 6.5.2 Pareia Geyser

Pareia geyser is located on the southeast end of Waikite Mound (Figure 6.4). Through historical time it has only erupted for a few months or years at a time followed by years of inactivity. Pareia erupted during February to May 1981, then remained dry until several eruptions were observed during 27-29 December 1987. It then became dry again until August 1997 when it resumed regular eruptions. It has remained active until the time of writing, typically erupting 2-4m high for about one minute, occurring every half to one hour.

### 6.5.3 Papakura Geyser

This geyser is approximately 100m upstream of the Rotowhio Model Village and close to the Puarenga Stream (Figure 6.4). Papakura geyser was historically active until March 1979, when it ceased all boiling and geysering activity (Grant and Lloyd, 1980). It now appears to have ruptured its vent. Until 1979 it had only been known to stop playing on three occasions, twice in the 1920's and once in the 1950's, with each stoppage lasting only a few days or weeks (Cody and Lumb, 1992) (Figure 6.5). The dormant period in the 1950's was accompanied by water in the vent turning muddy and sandy material being thrown out. This type of phenomenon is very suggestive of its feeder fissures and conduits having been abruptly ruptured.

During the 1990’s and up until at least November 2001 it has remained only a weakly acid low chloride heated ground water pool, with no indications of ever recovering its previous water chemistry and activity.

### 6.5.4 Parekohoru and Korotiotio Springs

Parekohoru is a large circular spring vent about 6m diameter and located centrally in the Rahui of Whakarewarewa Village (Figure 6.4). The historical European name for Parekohoru is the Champagne Pool, which relates to the occasional fizzy ebullition and boiling surges. This type of activity ceased by the late 1979, although a few boiling overflows occurred following meat being cooked in the pool. Parekohoru also ceased all overflow for several days during July and August 1986, the only time this has been recorded.

Throughout the 1990’s and up to at least the time of writing in July 2001, Parekohoru has shown a gentle flow 2 ℓ/s at 96-97°C but has occasionally boiled and surged in a large overflow (about 15-20 ℓ/s) for a minute or less, with these episodes recurring approximately every hour. These boiling overflow surges resumed in 1989, after being absent for about 10 years from 1979-1989. A conspicuous feature of these boiling surges is the powerful percussive ground thumping that can be felt to 20m from the pool margins. By the late 1990’s and up until at least November 2001 it boiled and overflowed in huge surges of about 20 ℓ/s every 1-2 hours daily.

Korotiotio (Oil Bath Spring) is approximately 30m west of Parekohoru and is a series of seven small vents within an area of 3m x 10m. This spring was the original source of water for the Oil Baths of the 1890’s up until about 1978, when it ceased reliable overflows. At about this time outflow from Parekohoru was channelled to supply the Oil Baths. All of Korotiotio’s vents showed weakened overflows in late 1978 and stopped overflowing on several occasions in 1979. In 1980 all surface overflows ceased and have not resumed at the time of writing.

Frequent hydrothermal eruptions during the 1970’s and 1980’s occurred from Korotiotio’s vents and these eruptions may have created an underground outflow to the Puarenga Stream. Since about 1996 Korotiotio water levels have gradually risen so that by 2001 water level is about 0.1-0.3m below surface overflow level. Boiling is now restricted to the southernmost vent, with constant and powerful boiling, up to 1m high.

### 6.5.5 Roto-a-Tamaheke Thermal Area

East of Whakarewarewa Village the large hot lakelet Roto-a-Tamaheke occupies a broad shallow valley impounded by silica sinters deposited from numerous boiling springs (Figure 6.9). In historical times outflows from the lake and its surrounding springs have been altered by human intervention on many occasions and the boiling of its neighbouring springs have also ceased for years at a time.

In the 1930’s four different users competed for hot water out of Roto-a-Tamaheke and its adjoining springs, known collectively as the Ororea group of springs. These springs provided gravity flow down to the Ward Baths, on the site of what is today the Polynesian Pools in the Government Gardens. At the east end of the lake gravity flow also supplied the Spout Baths located between Roto-a-Tamaheke and the Puarenga Stream until the baths were demolished in 1940. At that time another channel out of the lake fed across the Puarenga Stream in a flume to the Geyser Hotel, now known as the Centra. At the western end of the lake, residents in Whakarewarewa Village drew off water to the Hirere Bath (or Down Bath) (Figure 6.9).

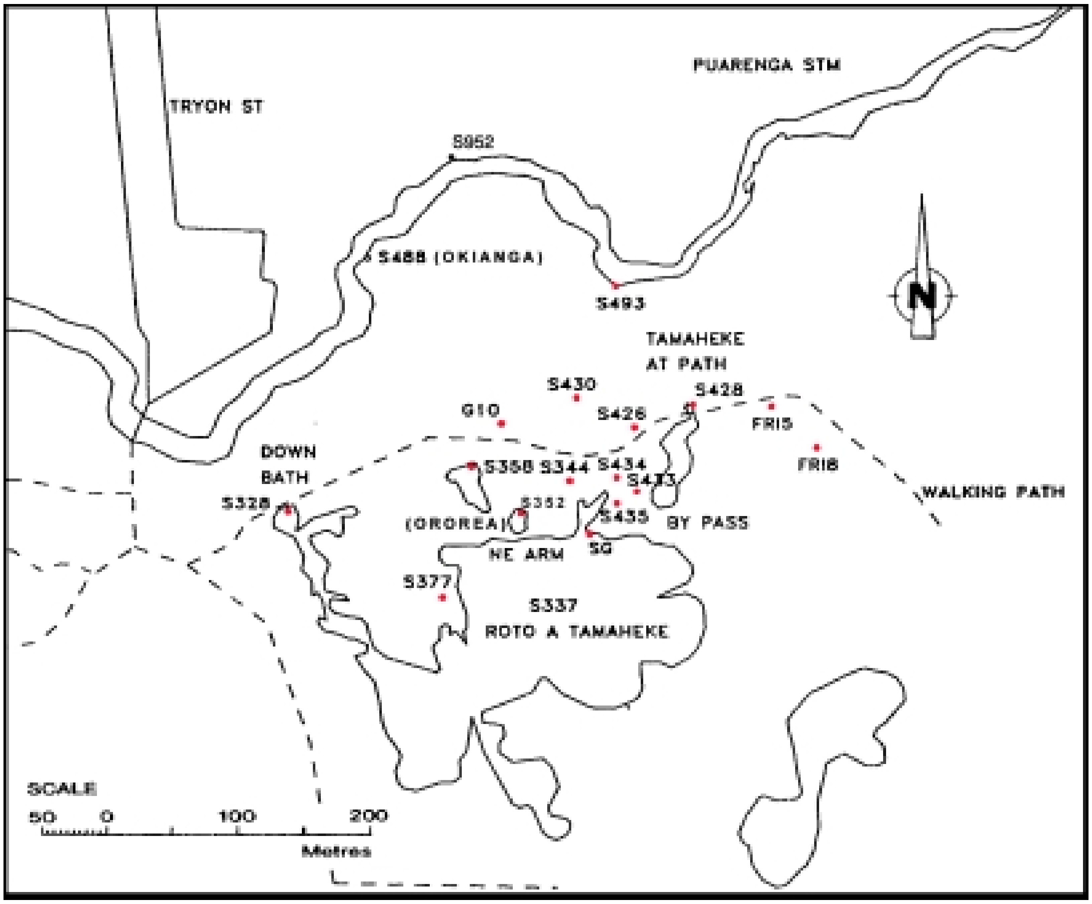


*Figure 6.9 Location of major springs in the Roto-a-Tamaheke thermal area east of Geyser Flat - Whakarewarewa.*

Disputes over the supply of hot water from Roto-a-Tamaheke led to very active building and destruction of dams and channels in the 1930's, which culminated in a series of hydrothermal eruptions over Labour Weekend of 1938. Following those eruptions the lake formed a new underground outlet and both the Ward and Spout Baths underwent increasingly more frequent interruption of flow until there was total cessation of all hot water supply (Modriniak, 1944). By early 1943, Roto-a-Tamaheke and its adjoining Ororea group of springs had all fallen below overflow and by 1944 the lake was about 2m below its previously "normal" overflowing level (Figure 6.10). In the late 1940's boiling overflows resumed until 1982 when the springs ceased overflow for one month. From 1982 to 1996 these springs resumed boiling overflows but with cessations in 1983 to 1987 and for approximately one month in 1991.

In March 1996 the Ororea Group of springs (S350-354; Figure 6.10) ceased boiling and flowing, and in March 2001 the western lakeside springs (S377 area) abruptly ceased boiling and flowing. By late May 2001 the Hirere Bath (Down Bath) could only be filled once a day instead of being constantly replenished with hot water. By June 2001 many pools around the northern and western margins of Roto-a-Tamaheke had fallen to 1.2-2m below overflow and had cooled, with no outflow at the eastern outlet nearest Forest Research Institute, and no boiling around the entire lake. This change is unprecedented since 1981 and is similar to the widespread collapse of boiling and flowing occurred from 1938-1945 (Modriniak, 1944). The cause of this cessation of hot spring activity is as yet unknown but it is contrary to the general field-wide trend of improved spring flows.

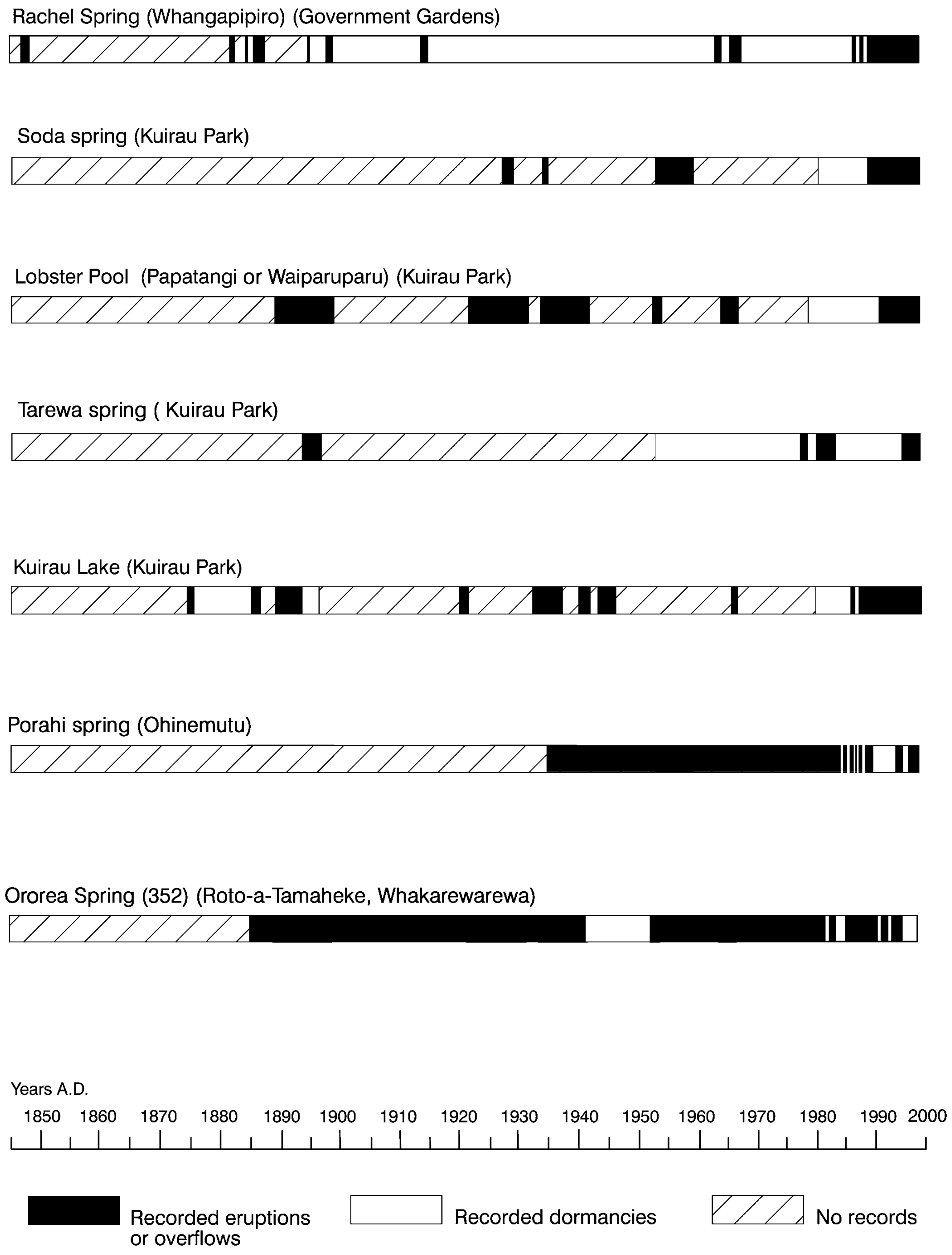


*Figure 6.10 Histograms of known hot spring activity from 1800-2000. Recorded as spring overflows.*

## 6.6 Kuirau Park and Ohinemutu Hot Springs

From 1989 to 2001 there has been resumption of thermal activity in Kuirau Park. Historical and post closure changes in the park have been generally described by Cody and Lumb (1992), Scott and Cody (1997) and also Scott and Cody (2000).

During the 1980's Kuirau Lake rarely overflowed and by 1987 the shores of Kuirau Lake were cloaked with dense groves of 25 year old kanuka. By 1989 Kuirau Lake resumed continuous hot (70-80°C) and alkali-chloride outflows of 7-20 ℓ/s (Figure 6.10), with an ongoing pattern of old vents refilling with hot water. The kanuka trees died due to the consistently higher water levels.

On the western side of Kuirau Park are the Tarewa Group of springs. These are a series of large sinter lined basins 5-8m diameter that form a chain of vents extending from Kuirau Park westward to Tarewa Road. These springs were known to boil and overflow at irregular intervals from the 1890's, but with many years of dry and cold vents (Figure 6.10). During the 1940's to 1970's activity became dormant in this area. Springs here ceased all activity in 1981 and the vents became infilled with soil and debris which progressively camouflaged the fact that they were dry spring vents.

Geothermal activity in the area was dormant through the 1950's to 1960's, and in the 1970's, building development commenced. In March 1998 the springs refilled and resumed boiling and over flowing. This resulted in four houses being removed or demolished.

Along the eastern side of Kuirau Park, parallel to Ranolf Street, hot spring and hot pool water levels have increased since 1987. This recovery is ongoing at the time of writing. The Jaycee Monument and Lobster Pool (Papatangi-Waiparu) area has filled and heated and many shrubs have been killed by hot waters from flowing alkaline springs. Ground heating has progressively killed shrubs and trees alongside the public footbaths supplied by Soda Spring,.

In the early 20th century Waiparuparu (or Lobster Pool) was popular as a public bathing place and the Radium and Soda Spring baths further south in the Park were also in use. However between 1941 and 1966, all these bathing springs had cooled down or dried up completely (Figure 6.10).

Further south beside Ranolf Street, in the area of Radium Bath, a large oak tree (45 yrs old) and several well established large rhododendrons and camellia trees have also been killed by thermal activity since 1998. The Toot and Whistle children's playground in the Kuirau Park has been fenced due to recently formed soft hot wet ground; and the bordering old netball courts have developed two large (about 2m and 7m diameter) hot flowing pools within the paved courts. In June 2001 the cricket pitch again formed a collapse hole, which is now filled with warm water.

The recent resumption and increases of geothermal activity at Kuirau Park has been progressive and ongoing. Hot waters are heating, rising and beginning to boil after many decades without hot waters at such shallow levels. A dramatic hydrothermal eruption from an unnamed turbid acid pool (Spring No.721) occurred on the afternoon of Friday 26 January 2001. This pool is about 100m west of the Jaycees Fountain and Monument. The eruption lasted for about 4½ minutes, reaching a column height of an estimated 100m or more and throwing out a carpet of ejected boulders and muddy rubble, which was dispersed mostly in an easterly direction.

Approximately $1200m^3$ of debris was ejected in this 4-minute interval, with blocks up to 1m diameter being thrown 70m away. A crater of about 15m diameter remains and the ejecta have been left on site as a tourist feature.

Ongoing changes to surface activity are not restricted to Kuirau Park but are also progressively occurring throughout Ohinemutu. In Ariariterangi Street, a modern home has been abandoned due to boiling beneath the concrete floor; nearby a neighbour has lost several large trees due to scalded roots. In Whittaker Road a hot pool began overflowing and killing surrounding lawns.

## 6.7 Government Gardens, Sulphur Bay and Ngapuna

Few alkali-chloride flowing springs have ever existed in this area in historical times. Upflows of geothermal waters do occur but generally undergo mixing with lake waters to produce turbid acidic waters.

Rachel (Whangapipiro) spring is the largest alkali-chloride spring in Rotorua and is now the only remaining alkali-chloride spring in Government Gardens. Rachel spring has had many periods of flowing and non-flowing, boiling and non-boiling activity through historic times. Rachael has a circular vent about 7m in diameter and in prehistoric times Rachael overflowed to establish a sinter apron. Most of the sinter has been destroyed following modification to divert flow to supply nearby baths in the 1880’s. Since then water has been pumped from the spring to supplement the nearby public bath “Polynesian Pools”.

Oruawhata Spring (also known as Malfroy’s Geysers), has boiling alkaline waters at only approximately 2m depth, but no surface outflows or ponding have occurred since the late 1950s. The springs were modified by Malfroy in the 1890’s to provide a reliable hot water supply for the nearby Blue Baths, but the diversion of flow inadvertently caused spectacular geysering and they became known as Malfroy’s Geysers, that became a notable attraction until their demise in the late 1950’s. During the 1980’s one of these vents was dug open and the boiling alkaline waterlevels were recorded for several years. In the 1990s and to date, boiling still constantly occurs at 1-2m depths but no surface overflow or geysering has occurred.

Around Sulphur Bay and Ngapuna increased outflows of hot waters is noticeable but these areas have limited access. However, monitoring in the general area confirms that the Ngapuna springs have heated and increased outflows substantially since 1987-88. The hotter outflows have killed areas of adjoining manuka shrubs. By the late 1990’s and into 2001 all surrounding pools have heated substantially and the waters have become clear and alkaline.

## 6.8 Summary of Surface Activity Changes

Monitoring of thermal features has overall shown that activity is extremely variable. There has been considerable reactivation of springs since bore closure in some areas of the field e.g., Geyser Flat Whakarewarewa and Kuirau Park but dormancy of springs and features in other areas of the field e.g., Roto-a-Tamaheke.

These changes in activity can be influenced by both natural and human induced phenomena. Natural changes include high or low rainfall, atmospheric pressure, changes to conduits as result of sinter or sulphur build up and possibly earthquake activity. Human induced influences include changes to geothermal aquifer pressure by bore drawoff; the physical infilling or excavation of hot springs, diversion of flow; artificially draining ground waters and the diversion of rainfall infiltration as a result of stormwater management. Overall there has been considerable reactivation of activity since bore closure, however the 1992 to 2001 period has shown the greatest increase in activity.

## 6.9 Heat Flow in Whakarewarewa

One of the fundamental tenets of the Bore Closure Program in the late 1980's was that closure would both prevent the slow but progressive decline in natural geothermal activity, and return it to some state with natural output at a higher level at the same time as the pressure in the aquifer increased. As the monitoring program recorded the response of both the aquifer pressure and of the natural features, it became apparent that the immediate response of aquifer pressure to bore closure was fast, occurring over approximately two years.

The response of the natural features was much more equivocal, and rather slower. The response of features such as geysers and hot pools is difficult to assess on an individual basis. There are certainly some areas which show considerable increase in output, almost (in the case of Kuirau Park), to the point of alarm. In other areas the responses are more varied. Table 6.1 compares the outputs of natural features in late 2000 with those estimated in two previous surveys, in 1967 and in 1984 by Cody and Simpson, (1985). These all show dramatic improvements in the output since the late 1980's, with the thermal energy output generally approaching the outputs of the late 1960's.

In general the larger features have shown the greatest response, but with rather small and often reducing changes in their fluid output. Overall the outputs from the groupings of features are similar to those of 1967 and much larger than the outputs from the same groupings in 1984. Overall the total output of features has increased by 30% over the 1984 value, and is now within 10% of the 1967 value, which represents the most reliable estimate for discharge during a period when the field was only lightly stressed.

In 1992, Grant-Taylor and O'Shaughnessy reviewed the data describing inputs to the Puarenga Stream from the thermal output at Whakarewarewa. A heat flow survey in 2000 was targeted to give a more detailed picture of heat flow, but did not include chloride fluxes. The survey is able to indicate the contributions to the Puarenga stream by direct measurement of the stream flow, and by measurement of the flow from the major inflowing features. Table 6.2 makes this comparison.

*Table 6.1 Outputs (in kW above 0°C) of individual features in the Whakarewarewa area, together with sums for the subsections.*

| Spring No | Spring Name | 1967-69 | 1984-85 | 2000-01 |
|---|---|---|---|---|
| **TE TATUA FALLS/GEYSER FLATS SUBSECTION** | | | | |
| Spring 529 | Ngararatuatara | 137 | 132 | 41 |
| Spring 14 | | 38 | 38 | 127 |
| Spring 16 | | 38 | 0 | 4 |
| Spring 505 | | 39 | 4 | 418 |
| Spring 55 | Ngawharua | 225 | 217 | 256 |
| Spring 160 | | 4330 | 720 | 4,907 |
| Spring 108 | | 3 | 2 | 5 |
| Spring 110 | | 11 | 5 | 2 |
| Spring 115 | | 0 | 0 | 0.3 |
| Spring 76 | Te Horu | 0 | 0 | Avge=369 |
| Spring 172 | Blue Lake | 835 | 477 | 772 |
| Spring 20 | | 1270 | 497 | 219 |
| Spring 19 | | 0 | | 10 |
| **SUM** | | **8356** | **2092** | **7130** |
| **GEYSER FLATS/MEMORIAL BRIDGE SUBSECTION** | | | | |
| Spring 284 | Parekehoru | 1360 | 1100 | 588 |
| Spring 306 | | 15 | 137 | 113 |
| Spring 296 | | 7 | 5 | 1171 |
| Spring 166 | | 58 | 70 | 0 |
| Spring 185 | | 0 | 655 | 313 |
| Spring 502 | | 0 | 0 | 15 |
| **SUM** | | **2880** | **1967** | **2200** |
| **MEMORIAL BRIDGE/FRI SUBSECTION** | | | | |
| Spring 441 | | 2095 | 2760 | 145 |
| Spring 447 | | 963 | 1320 | 460 |
| Spring 290 | | 0 | 12 | 94 |
| Spring 328 | Te Kokonga @ Bathhouse | 2380 | | 5213 |
| Spring 333 | | 18 | 0 | 363 |
| Spring 488 | Oke geyser | 187 | 186 | 84 |
| Spring 427 | | 474 | 343 | 706 |
| Spring 428 | | 5630 | 5630 | 705 |
| Spring 952 | Blowout | | | 1938 |
| **SUM** | | **11747** | **10251** | **9708** |
| **Overall sum MW** | | **20.1** | **14.3** | **19.0** |

*Table 6.2 Direct and indirect measurement of the contributions to Puarenga Stream from the Whakarewarewa area in year 2000.*

| Site | Mass Flow l/s | | Heat Flow MW | |
|---|---|---|---|---|
| | Spring contributions | Stream measurement | Spring contributions | Stream measurement |
| Tatua Falls to Geyser Flat | 25.9 | 68 | 7.1 | 21 |
| Geyser Flat to Memorial Bridge | 8.3 | 113 | 2.2 | 13 |
| Memorial Bridge to FRI | 46.4 | -190 | 9.0 | -1 |

It is apparent that there are some considerable measurement discrepancies between the two different measurement sets. The spring contributions for the first two sections are certain to underestimate contributions to the stream since they represent only a small fraction of the geothermal outflow from the field. The relationship of the heat flow figures for the two methods is less clear. On the one hand, under assessment of the mass flow will cause a corresponding underestimate of the heat flow, while on the other hand loss to evaporation will cause the spring outputs to be higher than recorded by stream measurement.

For the Roto-a-Tamaheke catchment, approximately 65% of the flow is from the two features 328 and 428, so the variation should be much smaller. Values for output from Roto-a-Tamaheke are the sum of the these two features. In view of the discrepancies between spring contribution data and stream measurement, and the known difficulties in gauging stream flows, it seems sensible to adopt some other device to estimate total output from Whakarewarewa. One possibility is to scale the spring data on the basis of the much better estimated values in 1984. Table 6.3 shows comparisons for the years 1984, 1990 and 2000, broken into contributions from Roto-a-Tamaheke and all other sources between Hemo Gorge and FRI, with the 2000 data scaled from the 1984 data.

*Table 6.3 Contributions to the Puarenga Stream between Hemo Gorge and FRI.*

| | **Source** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Roto-a-Tamaheke | | | Puarenga Stream | | | Other Sources | | |
| Year | 1984 | 1990 | 2000 | 1984 | 1990 | 2000 | 1984 | 1990 | 2000 |
| Heat MW | 9 | 15 | 13 | 40 | 45 | 72 | 31 | 30 | 59 |

We know that the spring data for the year 2000 is a subset of the Whakarewarewa springs, and the values for the subset, and whole set, as measured in 1984 are well known from the data published by Cody and Simpson in 1985. The scaling is done by calculating the mass outflows for the springs for which we have data in the survey of the year 2000, then multiplying the heat flow for those springs by the ratio of total mass flow to mass flow for the same spring subset in year 1984 and 1990. This assumes that the subset of year 2000 is representative of the whole Whakarewarewa spring set. We also have to make the further assumption that the return is consistent over the whole area. Although this assumption is a little risky, there is no good reason to suggest that it would improperly overestimate a return. On a purely even base it could just as easily underestimate a return.

This scaling method introduces a discrepancy of 16% in the value for sources other than Roto-a-Tamaheke. It does suggest a very considerable increase in the deep geothermal output in the area, with most of the increase occurring since 1990.

A secondary check for reliability of the method, and on the stream gaugings is provided by a survey of chloride outputs from a similar selection of accessible springs providing input to the Puarenga Stream, and again requires comparison of the sum of the individual inputs and the incremental value of the chloride found as a difference between two flow stations. Data collected by Cody in a survey in early 2001, can be combined with flow gaugings to give the two required sets of figures. These are presented in Table 6.4.

*Table 6.4 Contributions to the chloride flow in Puarenga Stream between Hemo Gorge and FRI.*

| Spring No | | Spring Name | Chloride flow, grams per second |
|---|---|---|---|
| **TE TATUA FALLS/GEYSER FLATS SUBSECTION** | | | |
| Spring | 529 | Ngararatuatara | |
| Spring | 14 | | 0.16 |
| Spring | 16 | | |
| Spring | 505 | | 0.605 |
| Spring | 55 | Ngawharua | 0.367 |
| Spring | 160 | | 6.106 |
| Spring | 108 | | |
| Spring | 110 | | |
| Spring | 115 | | |
| Spring | 76 | Te Horu | |
| Spring | 76 | Blue Lake | |
| Spring | 76 | | |
| Spring | 172 | | 5.088 |
| Spring | 20 | | 0.005 |
| Spring | 19 | | |
| SUM | | | 12.383 |
| **GEYSER FLATS/MEMORIAL BRIDGE SUBSECTION** | | | |
| Spring | 284 | Parekohoru | 0.836 |
| Spring | 306 | | |
| Spring | 296 | | 1.751 |
| Spring | 166 | | |
| Spring | 185 | | 0.36 |
| Spring | 502 | | 0.008 |
| SUM | | | 2.955 |
| **MEMORIAL BRIDGE/FRI SUBSECTION** | | | |
| Spring | 441 | | 0.093 |
| Spring | 447 | | |
| Spring | 290 | | 0.183 |
| Spring | 328 | Te Kokonga @ Bathouse | 13.821 |
| Spring | 333 | | |
| Spring | 488 | Oke Geyser | 0.196 |
| Spring | 427 | | 2.423 |
| Spring | 428 | | 2.48 |
| Spring | 952 | THC Blowout | 5.286 |
| SUM | | | |
| **ADDITIONAL GAUGINGS** | | | |
| Form | A | Puarenga@ Hemo Gorge | 12.3 |
| Form | E | Puarenga @ Memorial Bridge | 65.9 |
| Form | F | Puarenga @ FRI | 84 |
| Form | G | Puarenga @ S.H. 30 | 90.3 |
| Form | C | Puarenga @ Whakarewarewa Bridge | 12.9 |
| Form | D | Puarenga @ Bridge by Pohutu Geyser | 18.1 |

It is immediately apparent that there are some large discrepancies between the two methods. For instance, the Te Tatua Falls to Geyser Flats plus the Geyser Flats to Memorial Bridge subsections have by the summing method about 16 g/s, and by the total increment system nearly 54 g/s. In part these discrepancies can be traced to inadequate data sets.

For springs where chloride data is available, the mass flows from springs measured represent only about 3% of the total flow that enters the Puarenga Stream in the same section. It is not clear how much of this extra flow (amounting to some 500 ℓ/s) is contributed from geothermal sources. The contribution between Memorial bridge and FRI is overestimated slightly by the summing method (24 g/s against 18g/s respectively). In this section, the contribution becomes even less clear. Despite an input of about 41 ℓ/s from springs listed in the table above, (that is the springs for which there is available chloride data), there is a net reduction in flow between Memorial Bridge and FRI. This lends weight to a previously expressed concern that the flow data indicated a flow loss in that section of the stream (Mark Stringfellow pers comm., 2001).

Overall, it becomes apparent that despite the importance of this portion of the Rotorua Geothermal Field to tourism and other values, the processes that are occurring here are only poorly understood.

# Chapter 7: Modelling of the Geothermal Field

## 7.1 Introduction

Modelling is a way of describing the features of a field in a way that can be used to predict behaviour of the field under circumstances that cannot be established from monitoring data alone. The first task of modelling is to develop a conceptual model that summarises data, and identifies the important processes that control the flow of fluid, energy and chemicals. The model for the Rotorua geothermal aquifer has been constructed from available information collected from the field. Model input data for the Rotorua field has largely been provided from logs from private bores. These borelogs provide valuable geological, pressure and temperature data for the model.

## 7.2 Development of the computational Model for the Rotorua Field

The actual computational model is a set of equations that describe flow of mass and heat in a porous medium. The equations obey standard physical rules, the mass flow is analogous to the geothermal fluid having a particular temperature and therefore set of properties, and flows in a porous medium which represents the rocks that act as the aquifers. These equations allow the state of the field (pressure, temperature, enthalpy, etc) to be calculated.

Once the model is constructed its output can be calibrated with known field measurements. For example if the permeability of rock and flows are known, then pressure along the flow lines can be calculated. This is then compared with measured data to evaluate the success of the model. If there is a good match, the model is acceptable. If the match is poor, it must be adjusted and re-run until it matches all available data. This calibration process is strengthened as the amount of data for calibration increases. Improvements in calculation techniques, and a better understanding of the processes used in developing the conceptual model also improve the quality of the model.

## 7.3 The Conceptual Model of Rotorua

Scientific data for the field provides an overall description of the processes occurring. Water and gas chemistry data provide the basis for conceptual models of processes that water undergoes as it boils, mixes or interacts with particular rock types. Water chemistry and gas data also provide information on the oxidation processes that occur as the mineral rich geothermal waters interact with dissolved air in the surface waters.

Geological and structural information provides the basis for a hydrological model which describes permeability and fluid flow. Data for Rotorua is largely collected into three volumes, the Technical Report of the Geothermal Monitoring Programme 1982-1985; the Special Issue Volume 21 No.1/2 of Geothermics; and Environment B·O·P Technical Publication No.7 Rotorua Geothermal Field - Response of the Field since Closure (1987-1992). As well as these major compilations, data is also collected by Environment Bay of Plenty as part of field management requirements of the Operative Rotorua Geothermal Regional Plan for the field.

A general description of data that provides the basis for the present conceptual model as described here is:

1. The field is a region of hot water of about 15km$^2$. Structurally, it contains rhyolite domes in the west, with an ignimbrite layer in the east overlaid by generally impermeable sediments.
2. The area, particularly to the south east, has a number of faults, and surface out flows occur at the Whakarewarewa/Arikikapaka, Government Gardens/Ngapuna and Kuirau Park/Ohinemutu areas.
3. Pronounced gradients in chloride, bicarbonate and tritium indicate different near surface fluids in the east and west.
4. Estimates of pressure in the natural state, and measurements of the pressure and temperature distribution prior to and after bore closures are generally reasonably well known.
5. A shallow ground water aquifer above the field, that is strongly influenced by lake level, and responds very quickly to rainfall.
6. A shallow geothermal aquifer with a strong east-west component in the flow.
7. A general northwards flow of geothermal water that discharges into the lake bed.
8. Deep upflow of geothermal fluid into the geothermal aquifer beneath Whakarewarewa, and North beneath the Pukeroa dome area.
9. Mixing of geothermal water with surrounding cold ground water.

## 7.4 Computational Models

The first computational model was developed by Grant *et al.* (1985) and was aimed at describing the effect of withdrawal from the field on the natural outflow at Whakarewarewa. In the mid 1980's there was considerable concern at the apparent failure in Whakarewarewa. Therefore the output from the model that could be most easily related to this concern was a series of impact maps. These maps (Figure 7.1) used contours to describe the impact of abstraction of geothermal water on the natural outflow of geothermal water at Whakarewarewa.

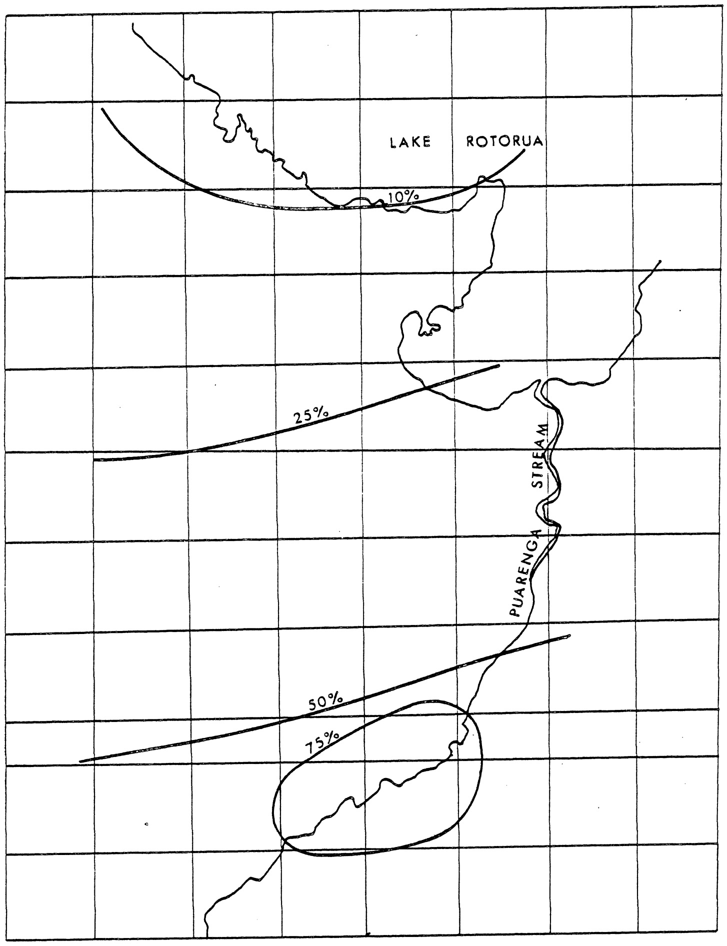


*Figure 7.1 Map showing the impact of withdrawal from the geothermal field on natural flow at Whakarewarewa (from Grant et al. 1985).*

### 7.4.1 **Tank Model – Bradford (1990)**

Bradford (1990) used a simple tank model to simulate the effect of rainfall on the levels observed in the geothermal aquifer. This model represents a very small part of the Rotorua Geothermal system. It attempted to identify the source of the cyclic variation of water level observed in the geothermal wells prior to closure. The model is a "leaky tank" where fluid leaks away (by evaporation or loss to growing plants). At a prescribed level (such as a rainfall high) the water overflows to a second tank, which represents a hold-up time in the ground. The water then passes to a third tank, which leaks a constant amount of water per unit time. This last tank represents a deeper reservoir. This model has as its output a curve that represents rainfall contributions to geothermal monitor bores. This output (Figure 7.2) taken from Bradford (1990) shows the simulated curve for ground water with level variations in the monitor bores M6 and M12.

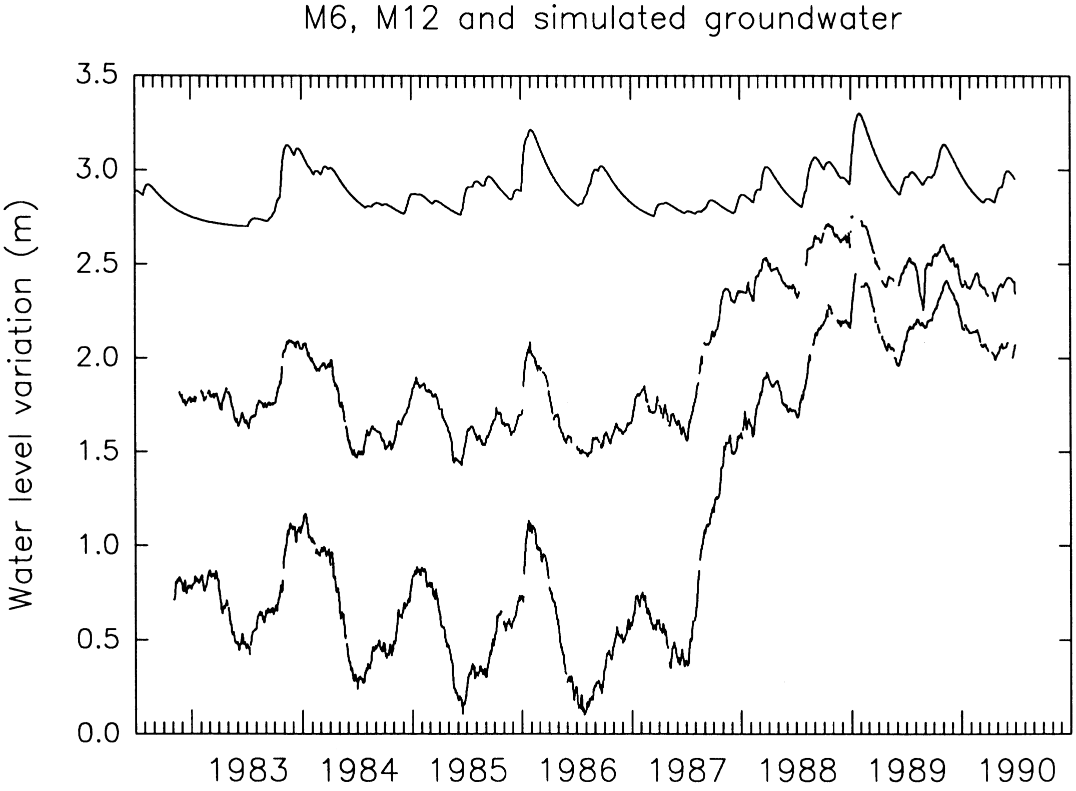


*Figure 7.2 Simulated water level variation due to rainfall compared with water level variation in M6 and M12 (from Bradford 1990). The bottom curve is the level variation of M6. The middle curve is the level variation of M12. the top curve is a simulated curve of possible rainfall/groundwater contributions to the level variation of Monitor bores.*

Three features are immediately apparent from the Tank Model. Prior to closure the rainfall can account for a portion of the annual variation in some years. It cannot account for all the variation in any year, nor does it account for the annual variation in every year. After closure, (in this case data only runs to 1990), the rainfall component dominates the level record, suggesting that any short-term rises should be examined for rainfall effects when assessing their relevance.

Over the closure period, rainfall contribution is near constant, and does not account for the level rise in the geothermal aquifer.

### 7.4.2 Numerical Flow Model – Burnell (1992)

Burnell (1992) developed a numerical description of the shallow geothermal aquifer which simulated mass, energy and chloride flows in the natural state of the system. The model included vertical structure in the aquifer, thermal effects (including boiling), and chloride flows. This model successfully simulated the natural flows in the system, and is generally consistent with the inferred natural state. This model presented the results as contours of pressure (Figure 7.3a), temperature (Figure 7.4a) and chloride (Figure 7.5a), which can be compared directly with those of Grant (1985) Figure 7.3b, Wood (1985) Figure 7.4b, Stewart *et al.* (1992) Figure 7.5b respectively. Agreement is reasonable, differing in detail, but providing a test for the improved detail included in the model.

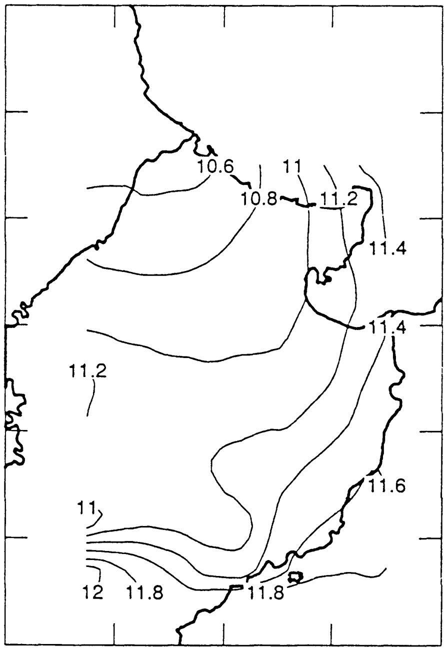


*Figure 7.3a Comparison of the output for steady state pressure, and the imputed pressure values from Burnell 1992 to Grant 1985 (Figure 7.3b).*

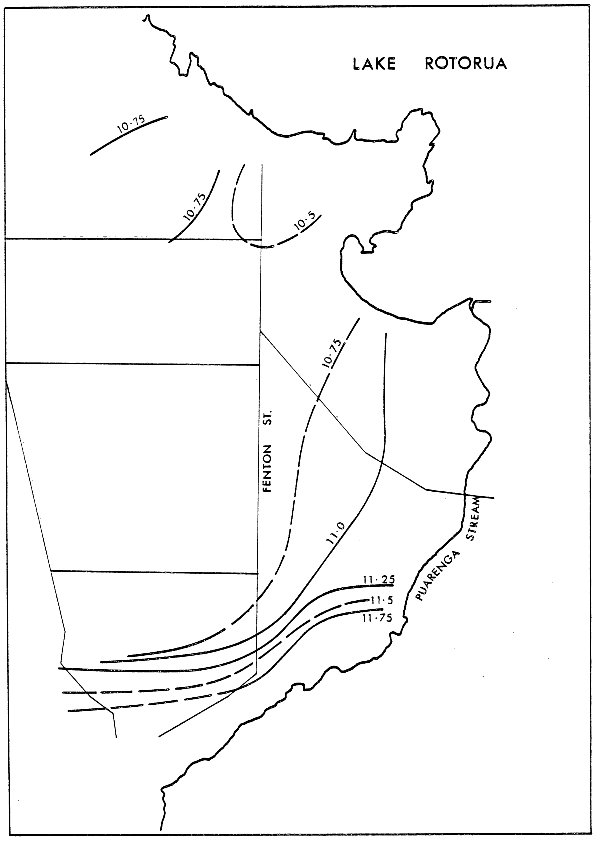


*Figure 7.3b Comparison of the output for steady state pressure, and the imputed pressure values from Grant 1985 to Burnell 1992(Figure 7.3a).*

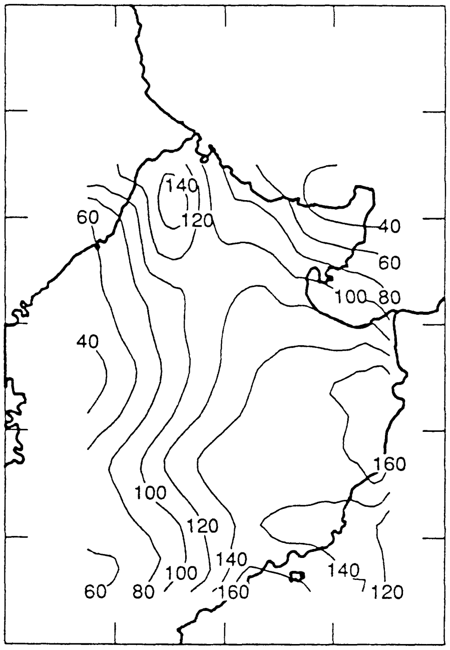


Figure 7.4a Comparison of the output for steady temperature and the measurements of Burnell 1992 to Wood 1985 (Figure 7.4b).

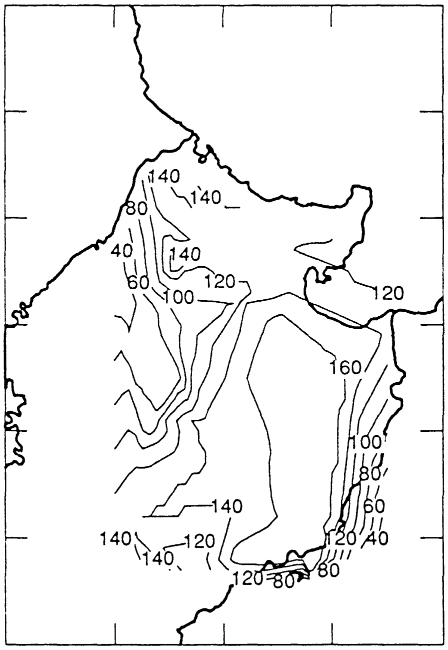


Figure 7.4b Comparison of the output for steady temperature and the measurements of Wood 1985 to Burnell 1992(Figure 7.4a).

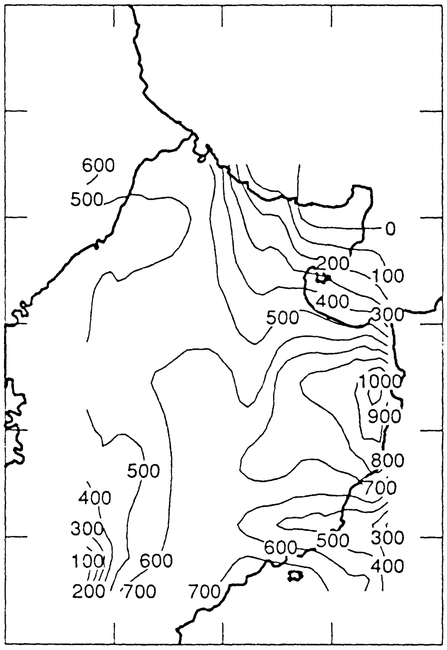


*Figure 7.5a* *Comparison of the output for steady state chloride concentrations and the measurements of Burnell (1992) to Stewart et al. (1992) (Figure 7.5b).*

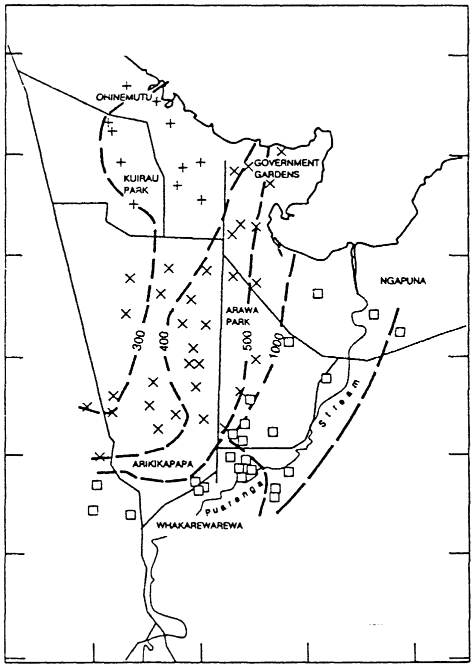


*Figure 7.5b* *Comparison of the output for steady state chloride concentrations and the measurements of Stewart et al. to (1992) Burnell (1992) (Figure 7.5a).*

### 7.4.3 Three Box Numerical Flow Model – Young and Burnell (1992)

Young and Burnell (1992), used a "three box" model to describe Rotorua. One box covers the rhyolite domes to the northwest, and most production wells. Outflows and inflows include production, natural outflows (Kuirau, Lake Rotorua, and ground water), and a hot upflow at Pukeroa dome. A second box covers the Ngapuna area to the east, with the natural outflow, and possible upflow at Ngapuna fault represented. The third box includes the large outflow at Whakarewarewa, including the deep hot upflow.

All the boxes are hydrologically connected to each other to allow horizontal flow. This model does not require accurate specification of the steady state, but is able to determine changes in outflows in a box in response to a change elsewhere. This type of model provides a very good check on the distributed models, which, while providing more detail require much better calibration. The box model was used to examine the response of different areas of the field to changes in production. This change could be brought about by increase in production, closure of bores, or reinjection. The model confirms generally high permeability, the highly sensitive response of natural flows to changes in reservoir pressure, and the low storage capacity of the system.

In terms of the effect of changes in withdrawal, the most relevant output of this model is shown in Figure 7.6, which shows the natural outflow from Whakarewarewa under two different scenarios. The scenarios are: decrease in production of 50 kg/sec in the rhyolite region to the northwest, and decrease in production in the northwest with reinjection into the southern area.

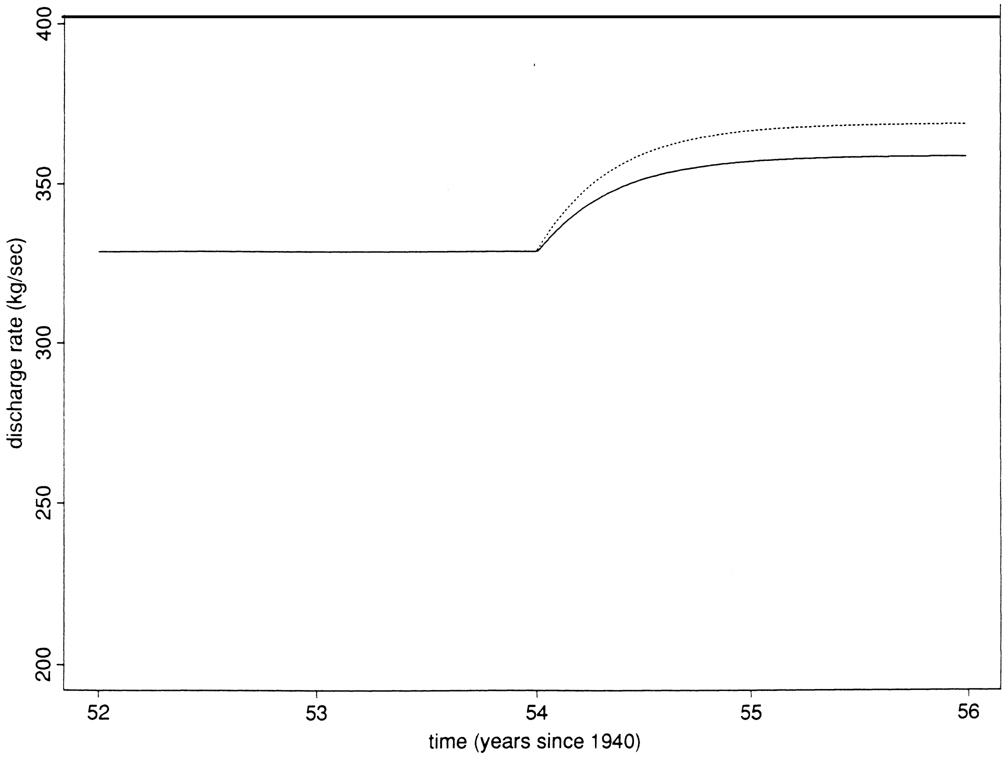


*Figure 7.6 Natural outflow from Whakarewarewa under two different management scenarios.*

### 7.4.4 Distributed Numerical Flow Model – Burnell and Young (1993)

Burnell and Young (1993) developed a "distributed" model that took advantage of improved computer software and hardware to solve a more complex model of the field, and to do this with more stringent tests on the acceptability of the output from the model. This model includes more detailed spatial variability in an attempt to match changes seen across the field and variations with depth. It was intended to quantify the impact of withdrawals from the field on the natural outflows at Whakarewarewa, Kuirau Park/Ohinemutu and Ngapuna.

The model was run using a modified version of MULKOM software that simulates coupled transport of liquid, vapour, heat and chloride in a porous medium. The model is able to provide good agreement with measured temperature and pressure data, changes to the outflow of Whakarewarewa which match inferred changes, pressure changes in the aquifer which match inferred changes, and changes in temperature and chloride concentrations which are consistent with the data.

The model suggests that as a result of the closure programme the flow from the reservoir into Whakarewarewa would increase from 190 kg/sec to 275 kg/sec (the actual data shows an increase from 200 kg/sec to 300 kg/sec), and an outflow at Kuirau Park/Ohinemutu increasing from 0 kg/sec to 15 kg/sec of 180ºC fluid (the measured value in 1993 was about 40 kg/sec, including a large ground water dilution component).

An updated version of the distributed model was used by Burnell and Young (1994) to evaluate the impact of ten scenarios using different withdrawal patterns for the field. Using the simulator TOUGH, and data collected by the monitoring programme and from other projects, the model tested the impact of reinjection, increased extraction, reduction of extraction to zero, and increasing extraction in the central business district. This material formed part of the input to the management plan for the field. This model was subsequently revised by Burnell (1998) to test a set of scenarios primarily associated with the use of the ICBF as a demarcation line for withdrawal policy. The model does not perfectly reflect the parameters of the field that are thought to have existed at the preclosure state, but give reasonable natural state results, and response to closure behaviour. However the model confirms that closure within the 1.5 km zone was important for recovery at Whakarewarewa, and that the impact of withdrawal on flow at Whakarewarewa is proportional to the distance from Whakarewarewa.

## 7.5 Comparison of the Predictions of the Various Models

The different models were not always aimed at producing the same output. However there has been general concern about the effect of withdrawal on natural features. Consequently models have been operated to evaluate these changes and so it is possible to make some comparisons. Table 7.1 lists the outcome predicted by the various models for scenarios as tested. Because the models were usually developed for different purposes, the outputs are not perfectly comparable, but some very strong correlations occur.

Table 7.1 Predictions of various models under different scenarios.

| Model | Scenario modelled | Model outcome | | | |
|---|---|---|---|---|---|
| | | **Flow at Whakarewarewa** | **Heat Flow at Whakarewarewa** | **Pressure in Field** | **Flow at Kuirau/Ohinemutu** |
| Grant (1985) | | | | | |
| Burnell and Young (1993) | Closure programme | 190kg/sec in 1986 → 275kg/s in 1993 | | | 0kg/sec in 1986 →15kg/sec in 1993 |
| Young and Burnell (1993) | 100kg/s production increase in city | 50kg/s decrease | | | |
| | Closure as made | 200kg/s in 1986→ 330kg/s in 1993 | | 1.0 to 3.0m head | |
| | 50kg/s decrease in production | 30kg/s increase in flow | | | |
| Burnell (1998) | No change | | 241MW | | |
| | No closure in 1.5k zone | | 206MW | | |
| | Withdrawal south of ICBF | Impact of 80% | 236MW | | |
| | Withdrawal north of ICBF | Impact of 60% | 237MW | | |
| | Withdrawal north of 1.5k zone | Impact of 30% | 239MW | | |

# Chapter 8: Usage Changes

## 8.1 Introduction

This chapter discusses current geothermal usage patterns in Rotorua and compares them to information recorded for 1985 and 1992, where appropriate. Comment is also made on projected future changes in usage of the Rotorua Geothermal Field.

Absolute comparison between usage figures for 2001 and those recorded for 1985 and 1992 is problematical as different legislative structures have been in place over the sixteen year period. These different structures have set different authorisation criteria for geothermal use. For example, sites that did not need authorisation under the Geothermal Energy Act 1953 (such as sites with bores less than 61 metres in depth and less than 70 degrees Celsius) did not necessarily appear on formal records available for analysis in 1985 and 1992 as they were not considered geothermal. Such sites are now considered geothermal. Under the Resource Management Act 1991, certain exclusions from requiring resource consents, were in place until the Rotorua Geothermal Regional Plan (the Plan) becoming operative on 1 July 1999.

The Plan is the first management tool designed to address the Rotorua geothermal field as both an entire entity and as a control on all geothermal use irrespective of depth or temperature.

## 8.2 Changes In Usage

Existing patterns of use and changes in use can be described in terms of:

- Bore location;
- Bore numbers;
- Bore ownership;
- Total withdrawal;
- Net mass withdrawal;
- Distribution of withdrawal;
- Percentage of Reinjection;
- Down hole heat exchangers.

## 8.3 Bore Location

Figures 8.1, 8.2 and 8.3 show the distribution and density of geothermal bores in 1987, 1992 and 2001 respectively.

Changes between 1985 and 1992 are most evident as:

(a) an overall reduction in number of sites;

(b) a significant reduction in density of geothermal bores between Malfroy and Devon Streets where a large number of domestic bores were grouted in response to the imposition of the resource rental regime;

(c) the impact of the 1.5 kilometre closure zone is immediately apparent with mostly heat exchangers located within the zone. The non down hole heat exchangers in the zone are on limited term resource consents and when these expire the abstraction of geothermal fluid must cease;

(d) The concentration of wells along Fenton Street associated with motel and hotels.

Changes between 1992 and 2001 are less dramatic. Where changes are evident such as the number of sites within the 1.5 kilometre zone, this is less a case of new wells and more related to identification of sites which have been in operation since before 1992.

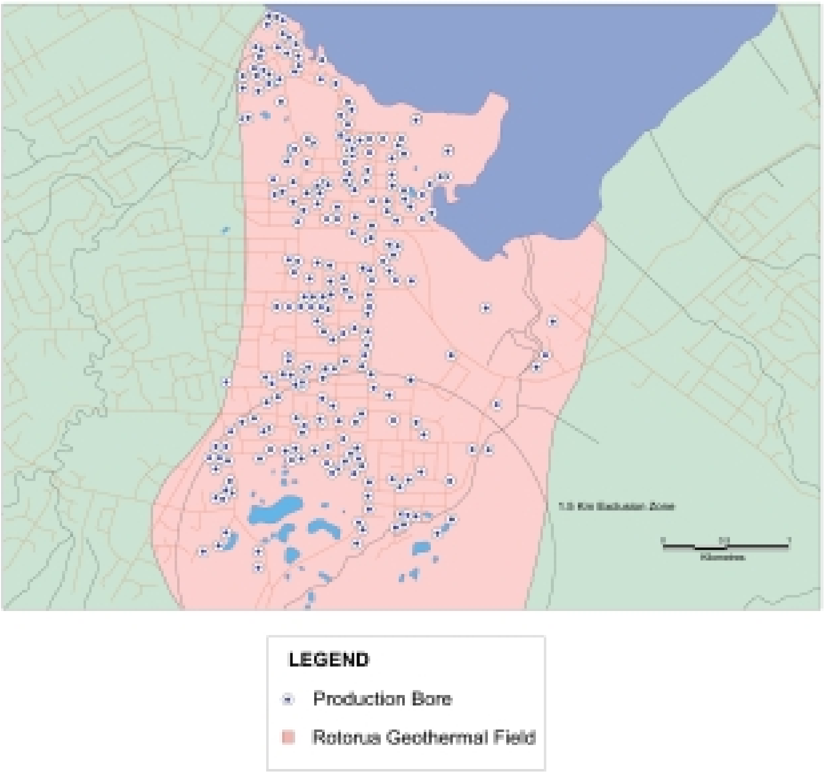


*Figure 8.1 Distribution and density of geothermal bores across the Rotorua geothermal field in 1987.*

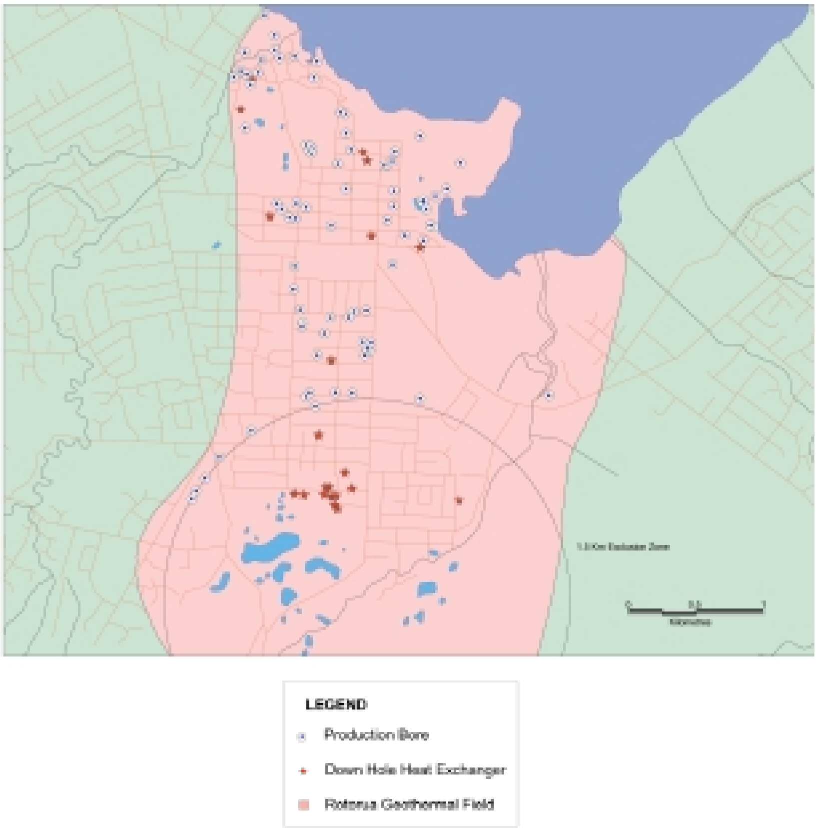


*Figure 8.2 Distribution and density of geothermal bores across the Rotorua geothermal field in 1992. Note the use of reinjection and downhole heat exchangers and the absence of production bores within the 1.5 km exclusion zone.*

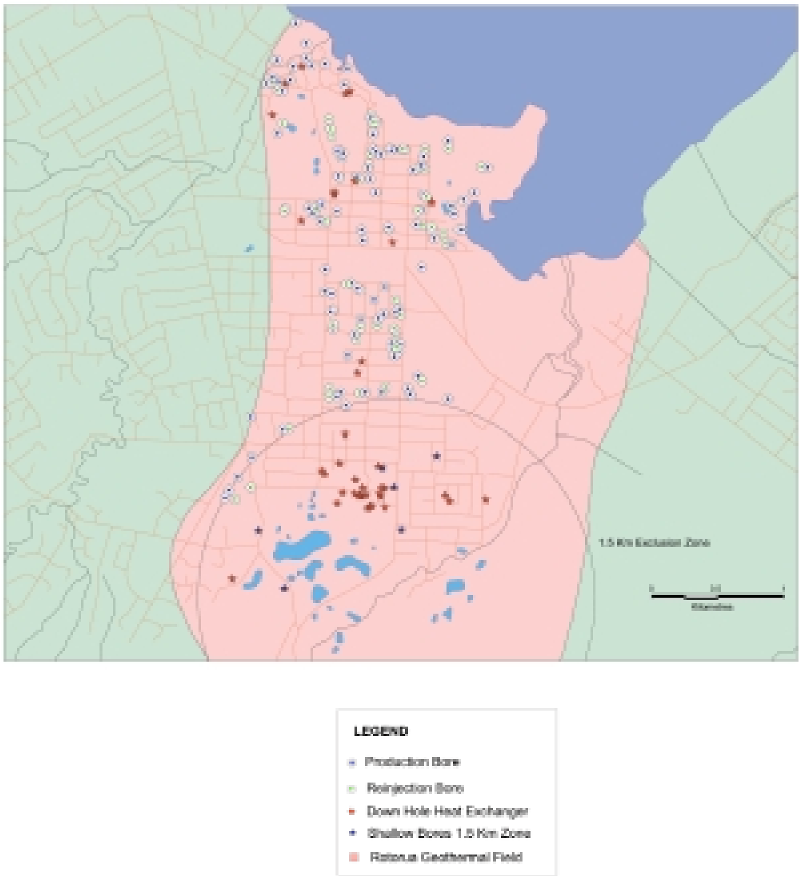


*Figure 8.3 Distribution and density of Geothermal bores across the Rotorua geothermal field in 2001. Note the increased use of reinjection bores and bores with downhole heat exchangers and the absence of production bores within the 1.5 km exclusion zone.*

## 8.4 Number of Production Sites

In previous descriptions, the number of bores in Rotorua has been used for comparative purposes. This however, is not a useful concept as a number of sites have back-up bores or as in the case of the Hospital have a number of back up production and reinjection bores. In addition, bores used for monitoring purposes were previously included in the tally of bores.

It is more useful to use the number of production sites as this gives a better assessment of the usage status of the field (Table 8.1).

*Table 8.1 Production sites in the Rotorua Geothermal Field – 2001.*

| | Number of Sites |
|---|---|
| Number of production bore sites | 144 |
| Number of reinjection bore sites | 68 |
| Number of down hole heat exchangers | 41 |

The number of sites have remained relatively static since 1992. New sites have been developed and a number of sites have been closed down and their bores grouted out. In particular, the major sites on the eastern side of the Puarenga Stream have closed down and other sites have been recently identified. The biggest single change is in the number of down hole heat exchangers (Figure 8.2 and 8.3).

## 8.5 Bore Ownership

*Table 8.2 Percentage of well ownership in the Rotorua Geothermal Field*

| | Years | | |
|---|---|---|---|
| | **1985** | **1992** | **2001** |
| Domestic Bores% | 50 | 54 | 54 |
| Commercial Bores % | 50 | 46 | 46 |

Table 8.2 compares the percentage of geothermal bores by ownership in 1985, 1992 and 2001. If a bore has any commercial user drawing from it, then it is classified as commercial. If the down hole heat exchangers are taken out of the tally, then of the sites extracting fluid, 65 percent are operated by commercial users.

## 8.6 Total Withdrawal

*Table 8.3 Geothermal withdrawal in Rotorua between 1985 and 2001*

| | Years | | |
|---|---|---|---|
| | **1985** | **1992** | **2001** |
| Total Withdrawal (tonnes per day) | 29,000 | 9,100 | 9,800 |
| Net Withdrawal (tonnes per day) | 27,500 | 3,800 | 1,900 |

Table 8.3 and figure 8.4 compares the total volume of geothermal fluid withdrawn from the field in 1985, 1992, and 2001. The 1985 total was estimated to be 29,000 tonnes/day, and by 1992 this had reduced to an estimated 9,100 tonnes/day. Current estimates are 9,800 tonnes per day and this includes 400 tonnes allocated to Polynesian Spa Limited for abstraction from the Whangapipiro (Rachel) Spring.

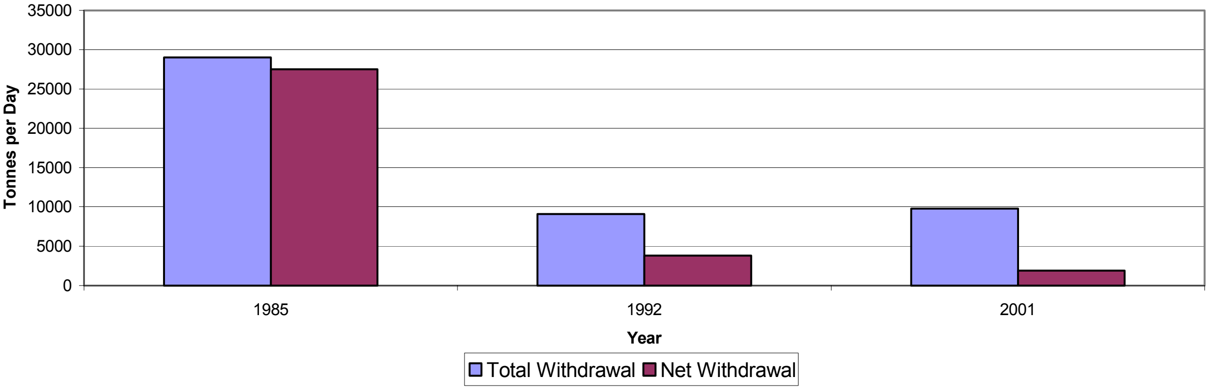


*Figure 8.4 Total and net withdrawal for the period, 1985, 1992 and 2001.*

## 8.7 Net Mass Withdrawal

The volume of geothermal fluid reinjected has risen, and this resulted in the reduction of the net mass withdrawal. This decline is illustrated in figure 8.4. The current net mass withdrawal is now only seven percent of the 1985 total.

## 8.8 Distribution of Withdrawal

Table 8.4 and figures 8.5, 8.6, 8.7, provide a breakdown of geothermal fluid extraction by commercial and domestic users. Completion of the closure program and imposition of the resource rental regime resulted in a major reduction in fluid withdrawal, particularly in the domestic sector between 1985 and 1992. Domestic withdrawal was once similar to commercial withdrawal but by 1992, domestic withdrawal had reduced to approximately 24 percent of total withdrawal. In terms of tonnage, this represents a reduction of 11,800 tonnes per day.

Current figures indicate that domestic withdrawal has dropped slightly to 23 percent. As discussed above, changes in the domestic sector have been static whereas there has been some increase in commercial activity. The increase in commercial activity is largely the result of the reinjection mitigation scheme.

*Table 8.4 Distribution of withdrawal in the Rotorua Geothermal Field*

| **Withdrawal** | **1985** | **1992** | **2001** |
|---|---|---|---|
| Domestic (%) | 48 | 24 | 23 |
| Commercial (%) | 52 | 76 | 77 |
| Domestic (tonnes per day) | 14,000 | 2,200 | 2,200 |
| Commercial (tonnes per day) | 15,000 | 6,900 | 7,600 |

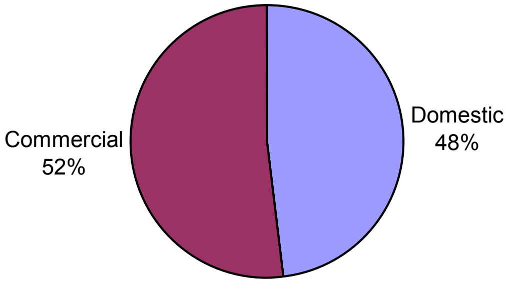


*Figure 8.5 Distribution of domestic and commercial withdrawal in 1985.*

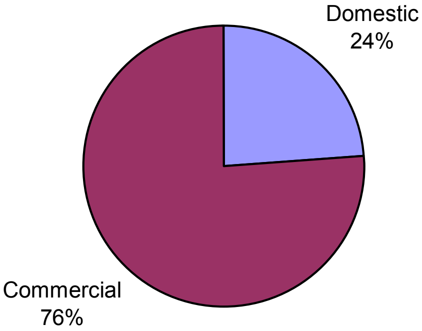


*Figure 8.6 Distribution of domestic and commercial withdrawal in 1992.*

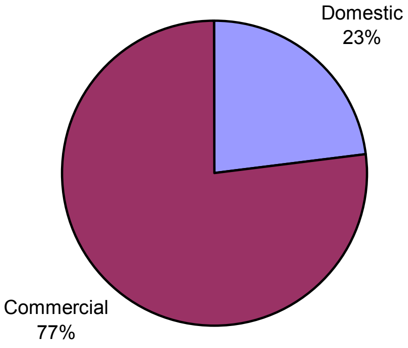


*Figure 8.7 Distribution of domestic and commercial withdrawal in 2001.*

## 8.9 Reinjection

Reinjection in the following discussion is, as determined in the Plan, the return of geothermal fluid to the aquifer from which it was extracted. Soakage refers to both disposal of used geothermal fluid to zones other than the source zone (usually to shallow soakage i.e., 10 to 20 metres) and to surface water courses.

Reinjection of sites in Rotorua is a corner stone of the management policies of the Plan. Modelling work undertaken during the formulation of the Plan indicated that conservation of mass within the Field was the key to maintenance of geothermal aquifer water levels and by association continued playing of geysers, springs and other surface outflow features.

The Plan requires that all sites, where it is neither technically unfeasible nor dangerous to reinject, to be reinjecting by 1 July 2002. The only exception to this, was where the owners of sites could claim an extension of time due to financial hardship. The owners of twelve sites applied for and were granted a time extension until 30 June 2004.

*Table 8.5 Geothermal waste disposal in the Rotorua Geothermal Field between 1985 and 2001*

| | 1985 | 1992 | 2001 |
|---|---|---|---|
| Reinjection (tonnes per day) | 1,500 | 5,300 | 7,500 |
| Non-reinjection (tonnes per day) | 27,500 | 3,800 | 2,300 |
| Reinjection (%) | 5 | 58 | 76 |
| Non-reinjection disposal (%) | 95 | 42 | 24 |

Table 8.5 and figure 8.8 demonstrate the increase in the total volume of fluid reinjected between 1985 (estimated 1550 tonnes), 1992 (estimated 5200 tonnes) and 2001 (estimated 7500 tonnes).

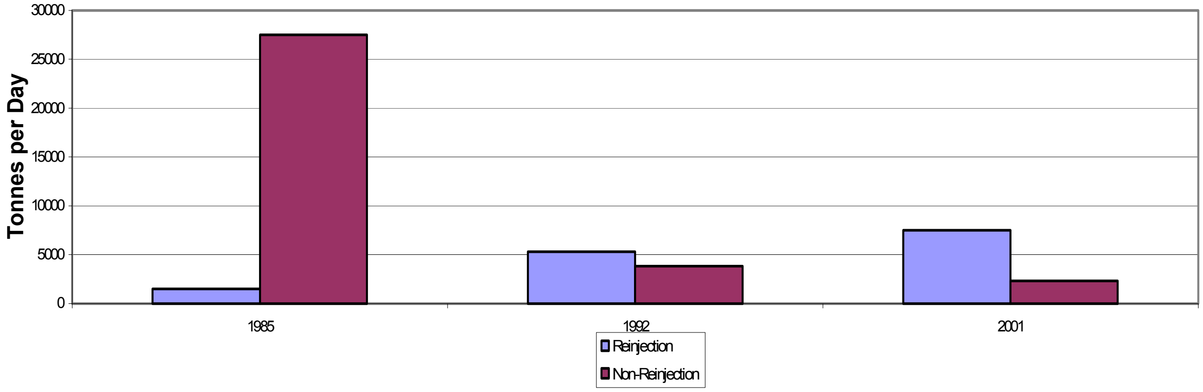


*Figure 8.8 Total tonnage reinjected between 1985, 1992, 2001.*

Of greater significance is the increase in the actual percentage of fluid being reinjected increasing from an estimated 5 percent in 1985 to 54 percent in 1992 to 76 percent in 2001 (Figure 8.9). Of the total withdrawal, 500 tonnes per day is permitted to be discharged to surface. Therefore, the actual percentage of fluid able to be reinjected is 81 percent.

There are currently 68 bores using reinjection pair systems with the majority (68 percent) operated by commercial users. Some production bores have multiple reinjection bores.

Reinjection has been slowly increasing in percentage since 1992 because of:

- Reinjection credit/environmental mitigation scheme;
- Change in ownership;
- Voluntary reinjection.

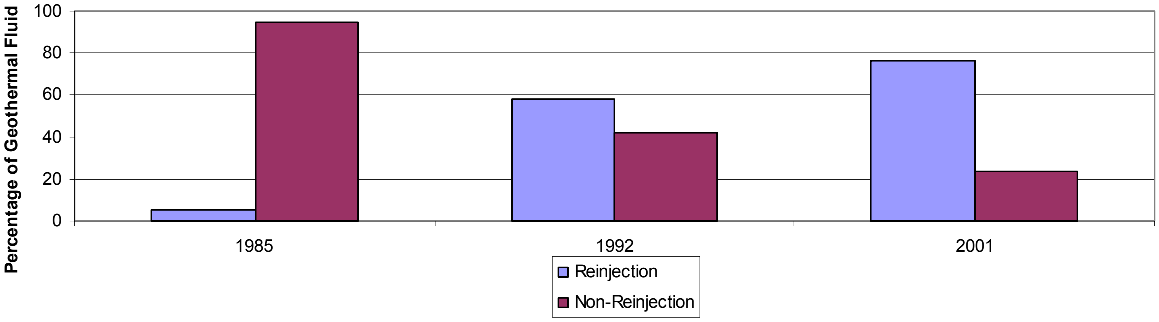


*Figure 8.9 Percentage of geothermal fluid disposed by reinjection and non-reinjection for 1985, 1992 and 2001.*

## 8.10 Reinjection Mitigation

To balance the needs of mass preservation/reinjection and needs of users, Environment B·O·P developed the reinjection credit scheme, which would allow new developments while achieving the objectives of the Plan (reducing the net withdrawal from the field and maximising reinjection). The scheme simply involves compulsory offsite environmental mitigation works and can be classified as an incentive economic instrument.

The scheme works as follows: A developer wishes to obtain an allocation of 200 t/d of geothermal fluid for a new hotel. The developer must arrange for the reinjection of 200 t/d at an existing extraction site or sites. These existing sites would be usually disposing of their spent geothermal effluent to ground soakage (i.e 10 to 20 m depth). The developer by arranging for reinjection of 200 t/d, earns a credit of 200 t/d which can be transferred to his new hotel site. The developer must also provide reinjection at the new hotel site. This results in an extra 200 t/d of geothermal fluid being extracted from the field but also results in an extra 400 t/d of fluid being reinjected. The net withdrawal from the field drops by 200 t/d.

The potential developer has a second option and that is to take control of an existing allocation and then transfer that to the new site. The criteria for allowing the transfer is grouting out of the existing bore and compulsory reinjection at the new site. The scheme has thus far resulted in approximately 850 t/d of extra reinjection to the field (reducing the net extraction from the field by approximately thirty percent), this has enabled four new major accommodation complexes to use geothermal fluid and five domestic group heating schemes that now have their spent fluid reinjected.

## 8.11 Changes in Ownership

Often as motels and/or domestic residences change ownership, due diligence by prospective purchasers reveals both the need for resource consent and more importantly the Plan requirements for reinjection prior to 1 July 2001. As this report is being written, four sites are preparing to have reinjection put in place as result of properties changing ownership. This will increase the reinjection tonnage by approximately 400 tonnes (or 4 percent).

## 8.12 Voluntary Reinjection

Since 1992, voluntary reinjection has also been taking place although at a far smaller scale than reinjection mitigation or changes in ownership. There appears to be a general acceptance amongst Rotorua geothermal users that reinjection is “the right thing to do”.

## 8.13 Down Hole Heat Exchangers

There are currently 41 known down hole heat exchangers in use, with the majority (88 %) operated by domestic users. In 1992, only 21 down hole heat exchangers were noted but it was recognised that significantly more could exist, particularly within the 1.5 kilometre mass extraction exclusion zone. The increase in down hole heat exchangers is a result of surveys within the 1.5 kilometre zone. These surveys continue and more down hole heat exchangers may be identified.

While it is generally recognised that increased use of down hole heat exchangers would be of benefit to the Field, there has been no new down hole heat exchangers installed in Rotorua since 1992. Indeed, the converse is true, a down hole heat exchanger system has been converted into a production-reinjection system.

Down hole heat exchanger systems continue to suffer from perceptions of poor performance. It is true that many existing down hole heat exchangers in use in the fields are “poor performers” however this is often a result of inefficient and/or older technology. Until more efficient down hole heat exchangers are put in place in the field and shown to be more effective, large scale increase in their use is unlikely.

## 8.14 Present 2001 Usage

From the above discussion, the current (2001) usage status of the Rotorua field is summarised in Table 8.6.

*Table 8.6 Summary of Geothermal Usage in the Rotorua Geothermal Field as at 2001.*

| | **2001** |
|---|---|
| **Total Withdrawal** | 9,800 tonnes/day |
| **Net Withdrawal** | 1,900 tonnes/day |
| **Domestic withdrawal** | 23 % |
| **Commercial withdrawal** | 77 % |
| | |
| **Number of production sites** | 144 |
| **Number of down hole heat exchangers** | 41 |
| **Percentage wells Domestic** | 54 % |
| **Percentage wells Commercial** | 46 % |
| | |
| **Reinjection** | 75 % of total withdrawal |
| **Soakage** | 25 % of total withdrawal |

## 8.15 Future Direction of the Usage in the Field

It is expected that future changes in usage patterns will follow those already established, in that the proportion of commercial use will continue to rise slowly and domestic use will decline. Total withdrawal is likely to increase slightly and net withdrawal will (following completion of the reinjection programme) remain close to zero. Bore numbers will increase slightly as the reinjection programme is completed but the increase is likely to be tempered by the closing of older bores.

In the past eight years, Environment B·O·P has only had three enquiries regarding either the reopening of old bores or the drilling of new ones for domestic purposes. It is believed there is now a greater awareness of the true cost of “geothermal” than in the past. Historically, geothermal energy was considered a ‘free’ low cost energy. Often costs such as ongoing maintenance and cost of replacement bores were not factored into the equation. In addition, requirements via the Plan for compulsory reinjection has also doubled the costs of drilling. As an example, a new site may have to pay upwards of $ 45,000 for drilling costs and perhaps another $10 – 20,000 for heat exchanger and reticulation system. Recent enquiries with Real Estate agents in Rotorua would suggest that unlike in the past, a property on “geothermal” may now only attract a premium of up to $5,000. The economics of moving to geothermal have become extremely marginal. In addition, it has to be recognised that geothermal energy can only provide a proportion of an average domestic property’s energy needs. Following reorganisation of the electricity sector, the average electricity account can contain upwards of 40 percent fixed charges, and therefore the use of geothermal energy to replace a portion of the electrical energy again becomes of marginal benefit.

It is believed that the commercial sector, particularly the accommodation sector will continue to see small growth. Following on from the successful conference in Rotorua on geothermal spa development, it was suggested that the trend in geothermal tourism is toward the boutique spa concept. This is where individual accommodation sites offer specialist spa related activities as opposed to the traditional large centralised spas such as Polynesian Spa. Having said that, the former Blue Baths have been refurbished and is offering geothermal bathing.

Large scale growth in the commercial use of geothermal fluid is to a degree, controlled by the number of beds available in Rotorua. The construction of further new large scale accommodation complexes, as found by overseas tourist accommodation trends (such as Rydges Rotorua and the Royal Lakeside Resort) are likely to require proportionally larger quantities of geothermal fluid.

In terms of bore numbers, no large change is expected. There may be some rationalisation of bores in the Ohinemutu area. This area has a large number of relatively inefficient shallow bores and there has long been a proposal to drill one large bore and set up a group heating scheme to service a large number of Ohinemutu properties. Such a scheme could see upwards of 15 bores closed. It is also expected that bores that fall due for replacement will not be replaced, particularly those not servicing group heating schemes or commercial properties, due to the marginal value of doing so.

Reinjection will also slowly increase over the next three years with a major increase expected to occur in early 2004 as the reinjection time extension granted to sites expires.

# Chapter 9: Summary and Conclusions

The management of the Rotorua Geothermal Field is defined by four time periods:

- Pre-bore exploitation – 1800 to 1950
- Exploitation of the field from bores – 1950 to 1986
- Bore closure and post closure field recovery phase - 1986 to 1992
- Field Management Plan and surface features recovery - 1992 to 2001.

Environment B·O·P is the field manager with implementation of the Rotorua Geothermal Regional Plan (the Plan). The key objective of the Plan is to protect and bring about field recovery and ongoing protection of geothermal surface features while providing allocation for various uses. The Plan sets out policy and rules to achieve this and requires Environment B·O·P to undertake monitoring and research necessary to support policy initiatives in the Plan. Results of this monitoring effort and technical investigations undertaken by Environment B·O·P and its consultants are summarised as follows:

(a) There has been a slow rising trend in the water levels of monitoring bores across the field. This increase is about 1m and cannot be fully accounted for by rainfall variation, bore closure or changes in usage.

(b) Annual rainfall recharge to the field has remained around a stable average value with rainfall highs in May-July 1998 which coincided with resurgence of thermal activity at Tarewa Road.

(c) A possible explanation for the slow rise in water levels is an increase in total output from the field. It has been shown by Kissling (2000) that it is possible for heat and mass output to vary by several percent on timescales of decades. This rise may have started early in the monitoring programme during the 1980's and would have been obscured by the downward trend in water levels in the field until 1986 bore closure.

(d) Since 1992 there has been a significant increase in the activity of surface features across the whole field. There has also been unprecedented eruption activity from Pohutu geyser and resumption of flow at a number of springs at Whakarewarewa together with reactivation of springs in other areas of the field that have previously been dormant (Tarewa Springs).

(e) The response of features such as geysers and hot pools is difficult to assess on an individual basis because natural and human induced changes can mask overall trends. Natural phenomena such as unusual rainfall intensities or shortages, earthquakes, and sinter or sulphur build up may cause variability in activity of surface thermal features. Human induced effects such as the physical infilling or excavation of features, diversion of fluid flow, artificially draining and the diversion of ground waters and rainfall infiltration and the local lowering of the geothermal aquifer pressure as result of bore drawoff also make it difficult to assess overall trends in activity.

(f) A heat flow survey of natural features at Whakarewarewa was completed in late 2000 in similar way to two previous surveys, in 1967 and in 1984 by Cody and Simpson, a (1985). Overall the total output for the surface features at Whakarewarewa has increased by 30% over the 1984 value, and is now within 10% of the value for 1967, which is the most reliable estimate for the discharge when the field was only lightly stressed.

| Heat flow surveys at Whakarewarewa | 1967-69 | 1984-85 | 2000-01 |
|---|---|---|---|
| Overall sum MW | 20.1 | 14.3 | 19.0 |

(g) Conceptual models were developed for the Rotorua field to summarise data, and identify the important processes that control the flow of fluid, energy and chemicals within the field. Computational models then developed described the effect of withdrawal from the field on the natural outflow at Whakarewarewa. The more recent distributed model by Burnell and Young (1994) was used to evaluate the impact of ten scenarios using different withdrawal patterns for the field. The model tested the impact of reinjection, increased extraction, reduction of extraction to zero, and increasing extraction in the central business district. This material formed part of the input to the management plan for the field. The model confirmed that closure within the 1.5 km zone was important for recovery at Whakarewarewa, and that the impact of withdrawal on flow at Whakarewarewa is proportional to the distance from Whakarewarewa (Burnell and Young, 1994) (Burnell, 1998).

(h) The computational models also suggest that as a result of the closure programme the flow from the reservoir into Whakarewarewa would increase from 190 kg/sec to 275 kg/sec (the actual data shows an increase from 200 kg/sec to 300 kg/sec), and an outflow at Kuirau Park/Ohinemutu increasing from 0 kg/sec to 15 kg/sec of 180ºC fluid (the measured value in 1993 was about 40 kg/sec, including a large ground water dilution component) (Burnell and Young, 1994).

(i) Usage patterns in the Rotorua Geothermal Field have essentially stabilised in the period 1992 to 2001 particularly when compared to the significant changes which occurred between 1985 and 1992. As reinjection slowly increases net withdrawal of geothermal mass is expected to decrease. Total withdrawal from the field is not expected to increase dramatically in the future.

(j) The general state of knowledge of the field is good although there are a few areas where the natural variability of geothermal features obscures detailed assessments of behaviour. Despite these difficulties (which are particularly pronounced in trying to quantify natural features) it is clear that the field has made a very significant response to the changes which were made in the late 1980's as the field moves to its new equilibrium state.

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