Rotorua Geothermal Field Management Monitoring Update: 2005

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Environment Bay of Plenty
Environmental Publication 2005/12
June 2005

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ISSN 1175 - 9372

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Acknowledgements

We would like to acknowledge the following contributors to this report;

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We would also like to thank P Dell for editorial comments and other Environment Bay of Plenty staff who assisted in the publication of this report. In particular M Glen for formatting of the report, R Funtelar for diagram draughting and K Heitia for printing.

Cover Photo: Roto-a-Tamaheke, Whakarewarewa Thermal Valley, Rotorua.

Reprint

Executive Summary

This report presents results of the monitoring information and technical investigations undertaken by Environment Bay of Plenty since 2001. The report provides a summary of monitoring and technical information on the current status of the Rotorua Geothermal Field (RGF). This information will assist the review of the Operative Regional Management Plan for the field commencing, July 2005.

Geothermal aquifer monitor bores (M – series) for the field have shown water level increases of 0.5 m between 1992-1999. This cannot be accounted for by variations in rainfall, but may possibly be caused by changes in usage, which occurred subsequent to the bore closures. From 1999 to 2004 water levels in monitor bores shows some short term variations but this is consistent with a stable pattern of geothermal aquifer pressures reaching equilibrium. Temperature profile monitoring also shows 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 to the 1m of water level change that has been observed in this monitor bore from 1992 to 1998.

Surface feature monitoring has indicated that the recovery of surface features has been a lot slower than the immediate response of aquifer pressure after bore closure. From 1992 – 2001 displayed the greatest period of surface feature recovery with the sudden reactivation of surface features in the northern field (Kuirau Park) in 1998. In the southern part of the field recovery has been mixed. Several features show positive changes, increased flows and temperatures. The primary geysers are erupting for longer periods, while some adjacent geysers have stopped erupting. The results of recent chemical sampling reflect similar variation of positive and negative changes.

As the field extraction/reinjection has been relatively steady since 2001, with a slight increase in reinjection it is likely that many of the surface features are now displaying aspects of their natural variability. Across the field there has been recovery, but this is not consistent. Features that responded quickly to the bore closures have not always remained hot or flowing. Many other features have been slow to show responses to the aquifer recovery. A possible explanation for the non-recovery of some features is that hydrothermal alteration processes may have damaged the feeder conduit systems.

Recent geochemical studies of selected surface features and bores shows that the fluids discharged in the northern area of the field at Kuirau Park now match those discharging in the early 1960s and it is likely that this part of the field is near full recovery. At Whakarewarewa, springs do not appear to be fed directly by a primary upflow and consequently the recovery has been mixed due to the influence of the hydrology between the upflow and the surface outlets.

The withdrawal of fluid from the shallow aquifers during the exploitation phase did not significantly change the composition or chemistry of the deep aquifer fluid. The shallow aquifer feeding the bores over the last decade shows relatively minor changes in reservoir chloride and small increases in heat (~16°C). This indicates that no deleterious processes are affecting the field.

Usage patterns in the field have continued to remain stable. Total withdrawal and bore numbers have remained relatively static between 2001 and 2005. Non reinjection production now only represents 10% of the total withdrawal. This increase is a result of an increase in reinjection from 7500 tonnes (estimated) in 2001 to approximately 8730 tonnes in 2005. The percent of total withdrawal discharged to soakage is now only 4 percent.

The model for the field has been updated in 2004 to bring it into line with current state-of-the-art geothermal modelling practice and to include new monitoring data. The 2004 model provides a good match to monitoring data and model results show that if production and reinjection is maintained at current levels, then pressures and outflows in the field will continue at current levels. In general, the field now appears to be in a stable dynamic state.

Nineteen usage scenarios were simulated using the 2004 reservoir model to assess the impact on the surface features at Rotorua. The impact was assessed by considering mass flows at Whakarewarewa and Kuirau Park and the amount of steam under Whakarewarewa. Scenarios with production outside the 1.5 km Exclusion Zone showed an impact on the outflow at Kuirau Park of more than 15% of the recovery from 1986 to 1990.

Scenarios with production and reinjection within 1 km of Pohutu Geyser showed an adverse impact on the amount of steam under Whakarewarewa. Adding new production and reinjection at a level 5% of the existing total production to a zone between 1 km and 1.5 km from Pohutu Geyser has only an impact on surface activity of less than 1% of the recovery from 1986 to 1990. Increasing the use of downhole heat exchangers by up to 200% within the 1.5 km exclusion zone was found to have a negligible impact on surface activity.

The scenarios considered here provide an indication of the likely response to increased production in various parts of the field. If changes to the Rotorua Geothermal Plan are envisaged then a more detailed set of scenarios should be developed and simulated to fully test the consequences of the anticipated change in the production pattern including combined effects of scenario usage.

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Chapter 1: Introduction

D A Gordon, Environment Bay of Plenty, Whakatane

Environment Bay of Plenty's Regional Management Plan for the Rotorua Geothermal Field is due for review in July 2005. 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 policies and rules to achieve this and requires Environment Bay of Plenty to undertake monitoring and research necessary to support policy initiatives in the Plan. The objective of this report is to provide a summary of monitoring and technical information on the current status of the Rotorua Geothermal Field (RGF). It is an update of the Rotorua Geothermal Field Management Monitoring reported in 2001 (Gordon et al 2001).

The Rotorua Geothermal Field (RGF) underlies much of the Rotorua city and the southern margin of Lake Rotorua. The field has an area of between 18-28 km^2 as defined by geophysical surveys. Surface geothermal activity is generally confined to three areas above 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 1.1).

The RGF is unique in that it contains one of New Zealand's last remaining areas of major geyser activity located at Whakarewarewa (Allis and Lumb, 1992) which is recognised to be of regional, national and international significance. On a local scale the field and associated surface features have strong social, cultural, intrinsic, and economic values (Environment Bay of Plenty, 1999).

The field is unique in that it lies beneath a major regional City, which has grown up and around the geothermal activity. The geothermal activity has historically and continues to attract people to live or visit the area. The present state of the field is a combination of the human activity and the intrinsic variability or nature of geothermal systems. This can be further defined by historic time periods when early use was made of surface activity for bathing, cooking and other traditional uses followed by field exploitation from drilling and abstraction of geothermal fluid from bores. These time periods are generally defined as:

- Traditional use and natural state -1800's to 1950;
- Intensive extraction fluid and heat 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;
- Dynamic equilibrium of the field - 2001 to 2005.

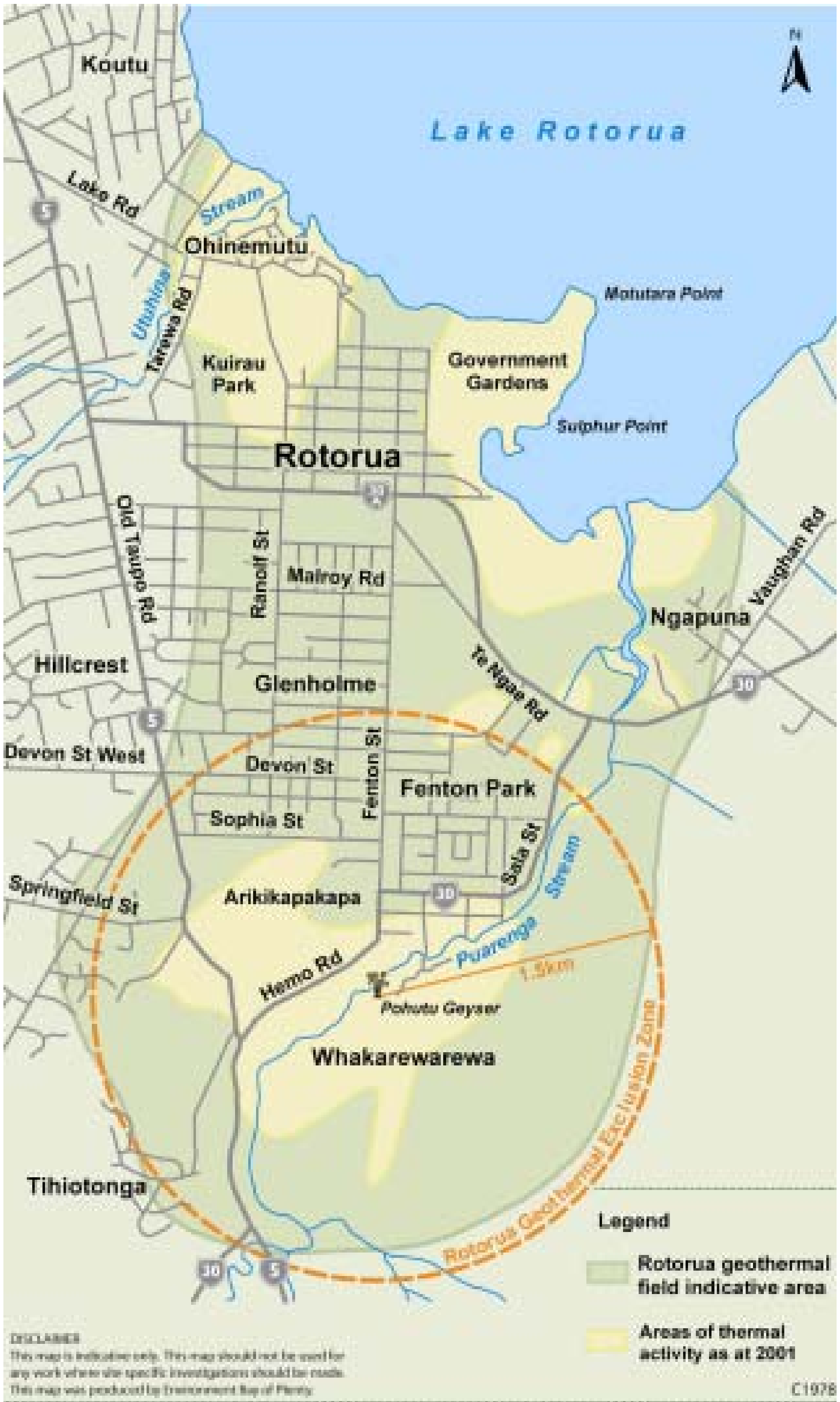

Figure 1.1 Extent of the Rotorua geothermal field as defined by the electrical resistivity surveys, and areas of surface geothermal activity. Also shown is the 1.5 km Rotorua Geothermal Exclusion zone.

1.1 Traditional Use and Natural State; 1800's to 1950

Extensive traditional use was made of hot water springs across the field for bathing, cooking and other uses. This resource continues to be of importance to the local people of Rotorua. Geysers, flowing springs 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. It was widely recognised at that time that geyser and thermal feature activity displayed a natural enigmatic variability, which is a phenomenon that is now widely accepted as a characteristic of geothermal systems.

1.2 Field Exploitation; 1950 to 1986

Geothermal energy was considered a cheap and convenient energy source during the 1950's and 1960's and this resulted in an increase in the number of bores drilled and used. Population growth and the energy crises in the 1950's and 1970's significantly contributed to further increases in bores drilled. (Ministry of Energy, 1985). Development of Rotorua City proceeded rapidly and this is likely to have influenced the field and surface thermal activity due to site levelling, drainage, 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 delegated this to the local Rotorua City Council under the Rotorua City Empowering Act 1967. This legislation focussed on the utility use of the geothermal field. No licences were issued during the 19 years the Rotorua City Empowering Act 1967 was in force and many bores were drilled and 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 surface geothermal activity, especially the geysers at Whakarewarewa and flowing springs in other areas across the field. 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 surface geothermal 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. A ban on drilling anything other than replacement bores within a 1.5 km radius of Pohutu Geyser (Figure 1). The government then 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. This work was carried out by government scientists at the former Department of Scientific and Industrial Research (DSIR) and Ministry of Works. 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).

1.3 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 taking action in 1986. This resulted in revoking local City Council control and 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 and re injection of geothermal fluid back into the field was promoted rather than waste fluid being discharged to shallow soakage. 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 significant pressure gains were apparent across the field. 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 including, 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.

1.4 Field Equilibrium and Surface Feature Recovery 1992 to 2001

This period was characterised by the greatest extent of surface feature recovery since the field closure programme and implementation of the regional management plan for the field in 1999. There was unprecedented eruption activity from Pohutu geyser at Whakarewarewa and the resumption of outflow from a number of springs at Whakarewarewa, together with reactivation of springs in other areas of the field that had previously been dormant.

The reactivation of features was particularly pronounced in the northern thermal area of the field at Kuirau Park. In 1998 the previously dormant Tarewa springs began to show renewed activity, some resulting in damage to property. A hot spring began flowing under the garage floor of home units at Tarewa Road, leading to demolition of the units and associated geyser activity from adjacent springs resulted in the removal of other dwellings. Investigation showed that one of the dwellings 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 highlighted 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 recovered. Environment Bay of Plenty 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.

During this period most of the geothermal monitor bores in the geothermal aquifer showed an increasing trend that could not be fully accounted for due to rainfall variation or changes in usage.

1.5 Field Dynamic Equilibrium; 2001 to 2005

The field has now reached a new equilibrium but the unexplained increasing trend in some geothermal monitor bores required further investigation as part of Environment Bay of Plenty's field management obligations set down in the Plan for the field. Environment Bay of Plenty commissioned consultants to review and implement a sampling programme to investigate if there have been changes to the chemistry of the geothermal aquifer. The chemistry of the aquifer is a useful tool for understanding possible changes in the deep source fluid, as these fluids may influence outflows in the field. The objective of this work was to collect new chemistry data for comparison with historic data. The results of this work are reported in chapter 5. Also, a soil gas survey was conducted by Geological and Nuclear Sciences (GNS) to assess the CO_2 flux from the field, the results of this work are presented in chapter 6.

Environment Bay of Plenty also commissioned an update of the 1994 computational model of the RGF so that the models performance could be assessed against new monitoring data and utilise state-of-the-art geothermal modelling practices. The model can then be used to assess the effects of scenarios like increases in fluid abstraction or reinjection. The results of the modelling work are presented in Chapter 8.

1.6 Field Management Plan

The Rotorua Geothermal Regional Plan was made operative in July 1999. The objective of the Plan is to ensure that the geothermal resource retained its value and potentials, while: protecting geothermal surface features and 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 Bay of Plenty, 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.

1.7 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 achieve this which include: a field model, monitoring water level trends, information from bore construction and testing, and the monitoring of chemical and thermal changes across the field.

1.7.1 Field Monitoring

Environment Bay of Plenty has a monitoring programme in place to gather information about the geothermal field and geothermal aquifer. An array of monitoring bores was inherited from the Government monitoring programme, many of the monitor bores continue to be maintained, however new bores have also being drilled to replace aging monitoring bores. Water level data has been collected from these bores and 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. Water level triggers for the geothermal aquifer have been set in monitor bores by the Management Plan for the field. These are defined as Strategic equilibrium water levels and have been set 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. The results of the field monitoring are presented in Chapter 3.

A programme of monitoring natural features has also been implemented by Environment Bay of Plenty to detect changes in activity at three main surface geothermal areas and in particular the highly significant geysers, springs and pools at Whakarewarewa. Surface features at Whakarewarewa and other geothermal 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 surface feature activity of key 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, interpretation of surface feature monitoring and aquifer data needs to be carefully considered when relating this to the state of the field. The results of this programme are reported in Chapter 4.

1.7.2 Field Modelling

Modelling is a useful tool that brings together theoretical understanding about the field and then this is tested against monitoring data and changes in bore use to make predictions of changes in the field. 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 Bay of Plenty commissioned Industrial Research Limited, to develop a computational model for the Rotorua Geothermal Field in 1994. This model is based on earlier conceptual and computer models that were developed during the government monitoring programme and revised models commissioned by Environment Bay of Plenty.

The 1994 model was used to test a variety of scenarios associated with setting the policy in the plan, especially with regard to abstraction and reinjection of thermal fluid. Results from this modelling 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 (Gordon et al 2001).

Environment Bay of Plenty recently (2004) commissioned an update of the 1994 computational model to check model performance against new monitoring data and bring the model for the field into line to current state-of-the-art geothermal modelling practice. The 2004 model was then used to assess the effects of 19 scenarios of limited increases in fluid abstraction and heat (down hole heat exchangers) the across field. The results of the 2004 field modelling work are presented in Chapter 8.

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Chapter 2: Physical Aspects of the Rotorua Geothermal Field

D A Gordon, Environment Bay of Plenty, Whakatane

The RGF 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 2.1). 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 1.1).

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 deepest geothermal bores, shallow ground water, and from natural features allowed interpretations of: water source, movement and mixing. This provided information on the control mechanisms for the local hydrology of the field.

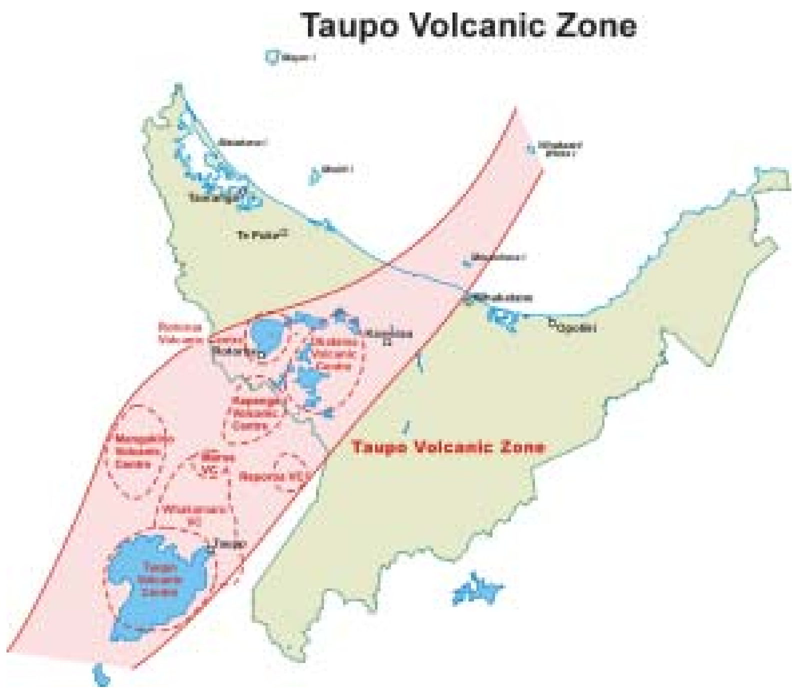

Figure 2.1 Location of the Taupo Volcanic Zone and Rotorua volcanic centre (after Houghton et al., 1995).

2.1 Geological Features

The RGF 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 Ngongotaha. 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, 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.

The shallow bores used to obtain geothermal water provide 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 its 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 (Figure 2.2)

2.2 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 spring alignments 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 of the 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 2.2).

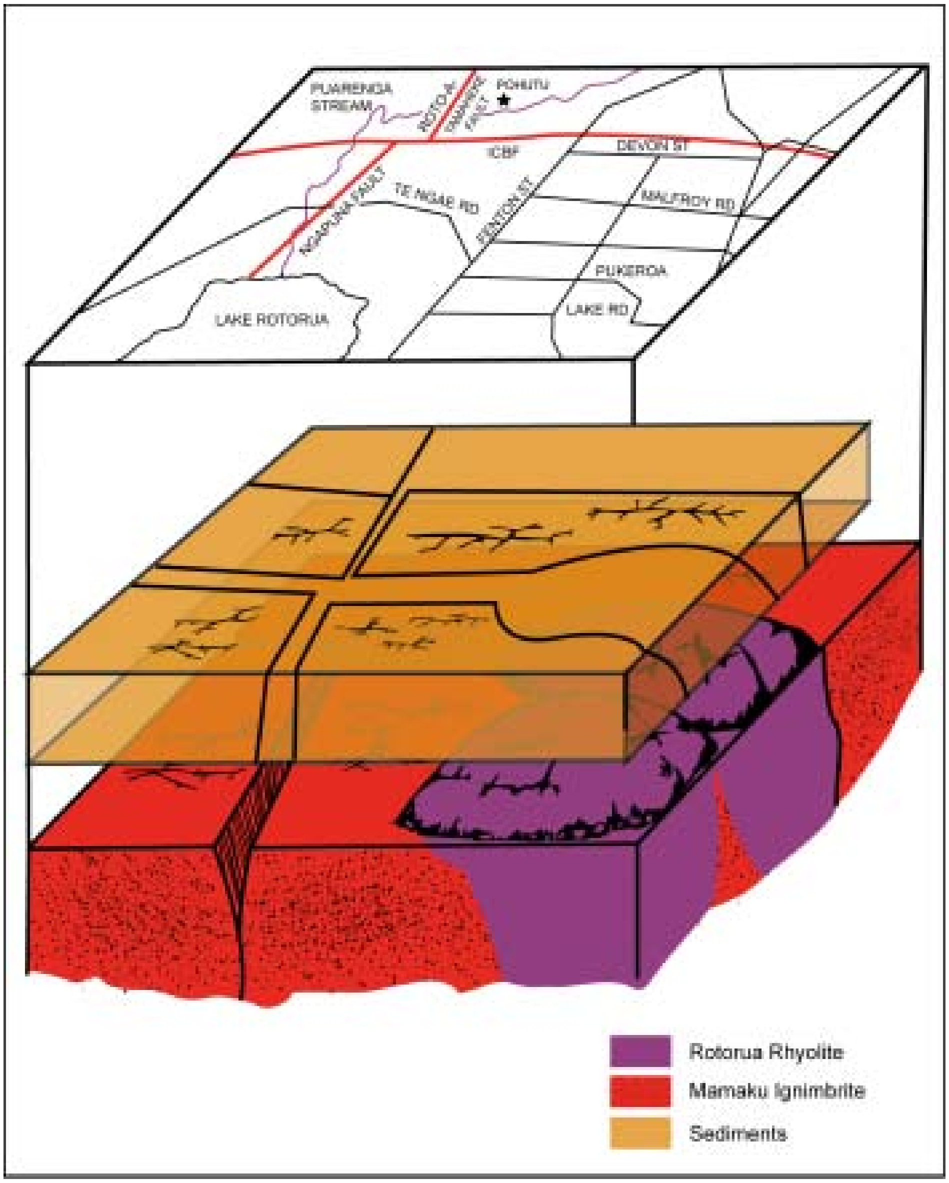

Figure 2.2 Block diagram showing the major geological and structural features of the field (after Drew 1985)

2.3 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 to 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 southeastern 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.

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. Mroczek et al present new chemical data from spring and bore sampling and compare this to existing data. The results support the previous work that indicates at least two separate plumes feed the shallow system. The primary upflow is to the east of the Rhyolite Domes, and then subsequently flows southeast to Whakarewarewa. The smaller separate upflow to the Kuirau area is chemically distinct. The Whakarewarewa springs do not appear to be fed directly by a primary upflow and consequently the recovery has been mixed as the hydrology between the upflow and the surface outlets are influencing conditions. The geological evidence (Wood, 1992) suggests that they are hydrologically connected. The shallow aquifer feeding the bores over the last decade shows relatively minor changes in reservoir chloride and small increases in heat (~16ºC). This indicates stability and no deleterious processes are affecting the RGF.

Whatever the merits of the two models it is apparent that the two natural spring areas, in the south and in the east, are interconnected. With the primary source of the fluids being in the east, and the fluids flowing southeast to Whakarewarewa. 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.

2.4 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 tend 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 2.3).

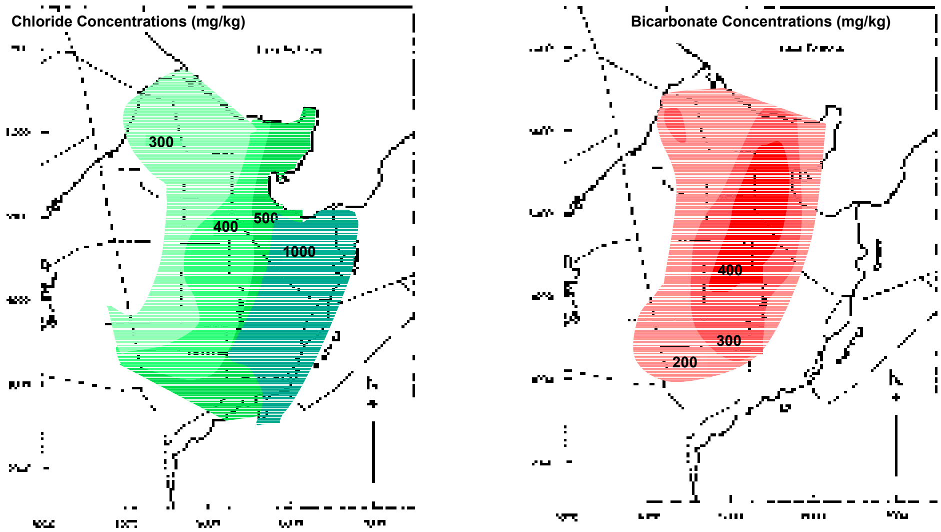

Figure 2.3 Chloride and bicarbonate levels in waters from geothermal bores in Rotorua (after Stewart et al. 1992).

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Chapter 3: Aquifer Monitoring

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3.1 Introduction

This chapter describes the data that has been measured in the geothermal aquifer, 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). Rainfall data is also described and the response of the shallow ground water aquifer.

Environment Bay of Plenty maintains a network of 5 geothermal monitor bores and five shallow ground water wells in the RGF (Figure 3.1). The monitor bores tap into various geology (ignimbrite and rhyolite lava) and aquifers, so that data is obtained from a good representation of the geothermal aquifer. (Table 3.1)

3.2 General Features of the Monitoring

The data obtained from the monitor bores can be naturally 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 field recovery;
- The post-closure phase of field equilibrium and surface feature recovery from 1992 to mid-2004 that was dominated by the greatest recovery of surface features.

In the following discussion each data set is presented in its entirety from the earliest records during the 1980s, to the present (Table 3.1). The data is discussed in terms of the three identifiable phases. The data sets are considered in the following order: monitor bores, groundwater wells, mass, chloride, heat flows and other natural features.

3.2.1 Monitor Bores

The most recent data set is that of Kissling (2005). Data for monitoring bores; M1, M6, M9, M12, M16, M17, M24 and M25 have been adjusted for barometric influences and are shown in Figures 3.2-3.9. Data for the entire period has been run as a single data set, so that long-term trends can be assessed. Where bores have failed, terminating the data set, the records are taken from the earlier publication of Bradford (1990). Details of all the Rotorua monitor bores are given in Table 3.1.

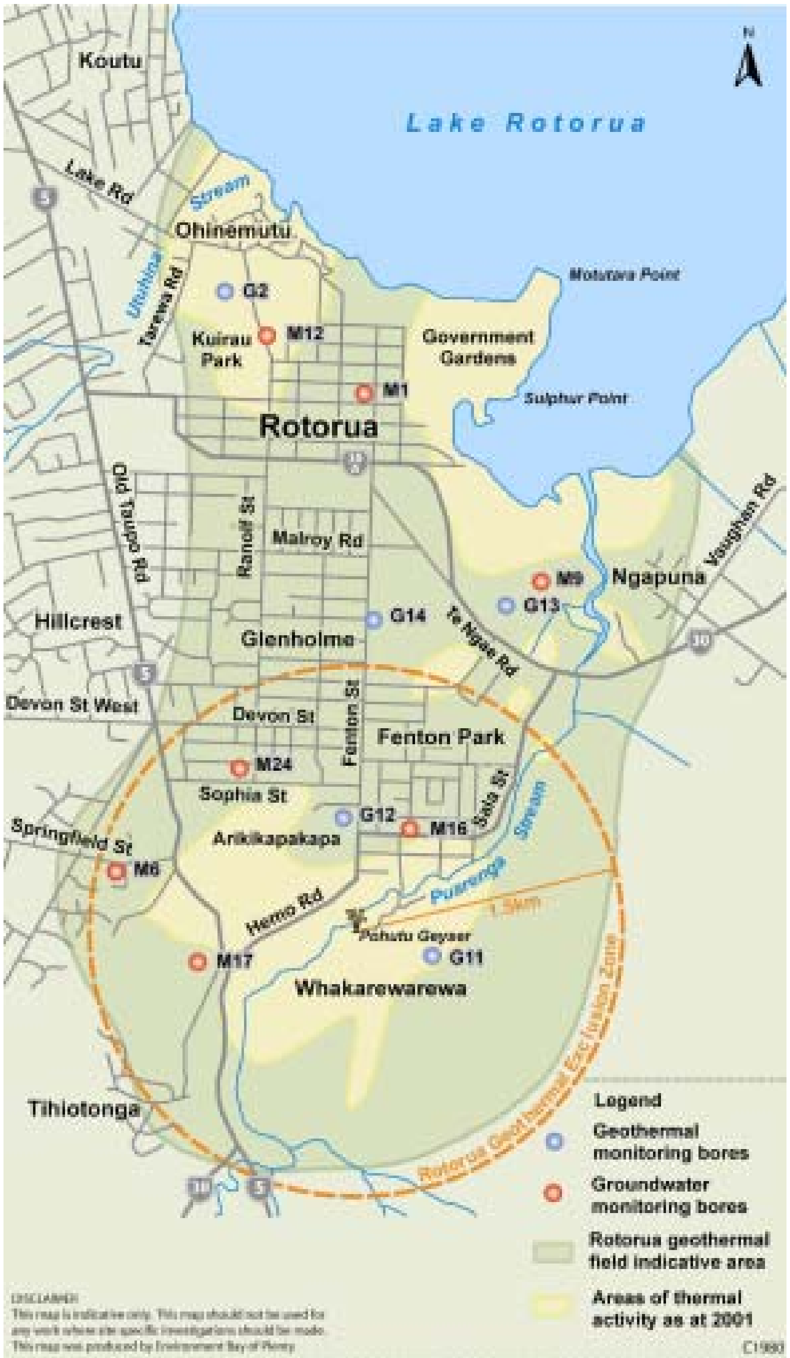

Figure 3.1 Current geothermal and shallow groundwater monitor sites in Rotorua.

Table 3.1 Locations, drilled depth, aquifer, geology, 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.

Name	RR No.	Location	Depth (m)	Casing Depth(m)	Aquifer Type	Data from	Data to
M1	305	Government Centre	64.0	43.6	Rhyolite	16 Nov 1982 11 Jan 1989	16 Jul 1985 Present
M3	462	Queen Elizabeth II Hospital	144.2	103	N/A	13 Dec 1982 17 Mar 1986	19 Jan 1986 22 May 1989
M5	684	Carnot Street	175.3		N/A	21 Oct 1982	25 Oct 1985
M6	777	Goodwin Avenue	256.0	122.0	N/A	29 Oct 1982 15 Aug 1995	23 Feb 1993 Present
M9	889	Sewage Farm	244.5	234.5	Ignimbrite	11 Sep 1984	14 Apr 1999
M12	886	Rotorua Public Hospital	75.0	N/A	Rhyolite	17 Nov 1982	Present
M13	868	Forest Research Institute	97.3	N/A	N/A	19 Apr 1983	2 Oct 1986
M14	409	Racecourse	70.1	N/A	N/A	15 Nov 1983	27 Sep 1985
M15	883	Victoria Street	134.0	93.5	Rhyolite	2 Dec 1983	7 Aug 1987
M16	624	Sala Street	156.9	116.4	Ignimbrite	25 Sep 1984	Present
M17	724	Waiariki College	156.1	87.2	Ignimbrite	7 July 1987	Present
M24	847	Carlton Street	133.0	95.7	Rhyolite	31 Mar 1993	Present
M25	1057	Sewage Farm	241.0	241.0	Ignimbrite	1 Mar 2003	Present
G2	N/A	Kuirau Park	6.0	5.0	Alluvial Sediments	17 Sep 1985	Present
G11	N/A	Whakarewarewa	6.0	5.0	Alluvial Sediments	17 Sep 1985	Present
G12	N/A	Arikikapakapa	8.0	8.0	Alluvial Sediments	17 Sep 1985	Present
G13	N/A	Sewage farm	6.0	5.0	Alluvial Sediments	19 Dec 1983	Present
G14	N/A	Racecourse	10.0	6.0	Alluvial Sediments	8 Sep 1982	Present
Lake	N/A	Mission Bay			N/A	Mar 1974	Present

N/A - Not available

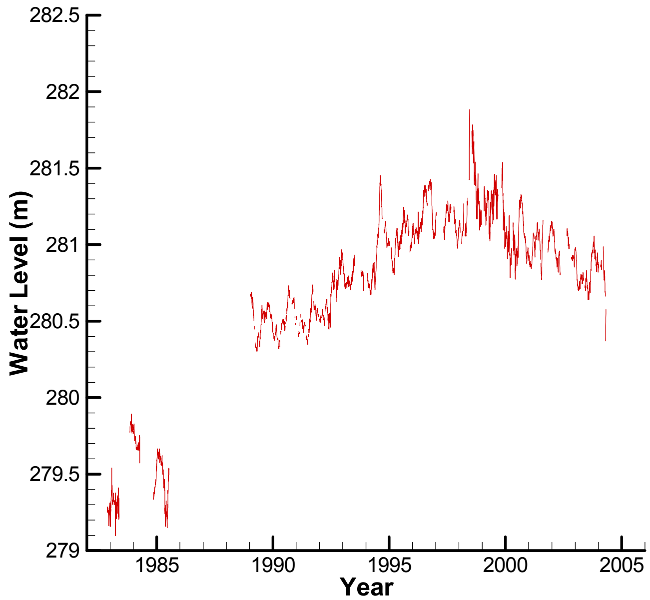

Figure 3.2 Water level in M1 with barometric pressure removed (from Kissling, 2005).

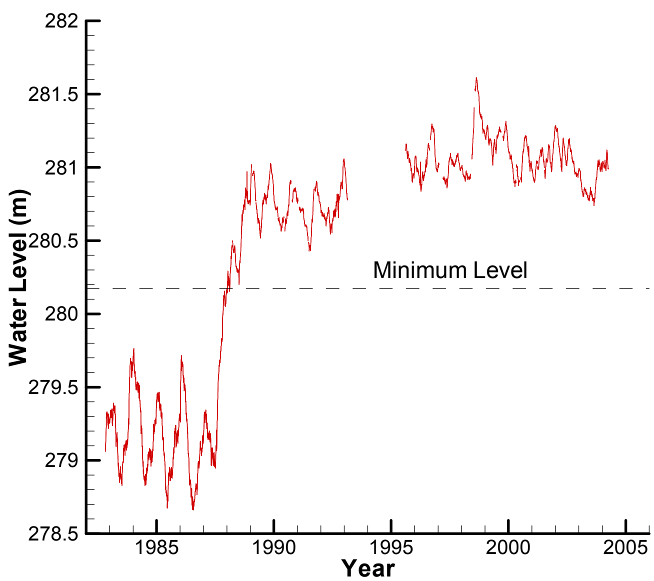

Figure 3.3 Water level in M6 with barometric pressure removed (from Kissling, 2005). Minimum level is the level defined in the Field Management Plan.

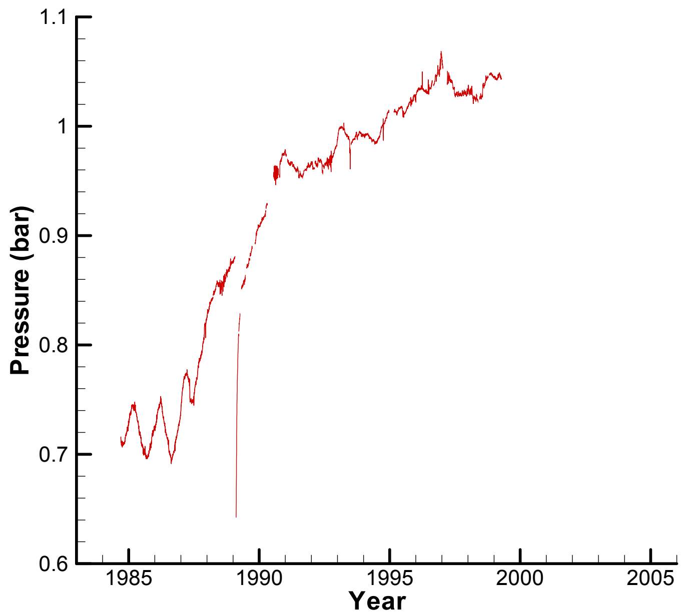

Figure 3.4 Pressure in M9 with barometric pressure removed (from Kissling, 2005).

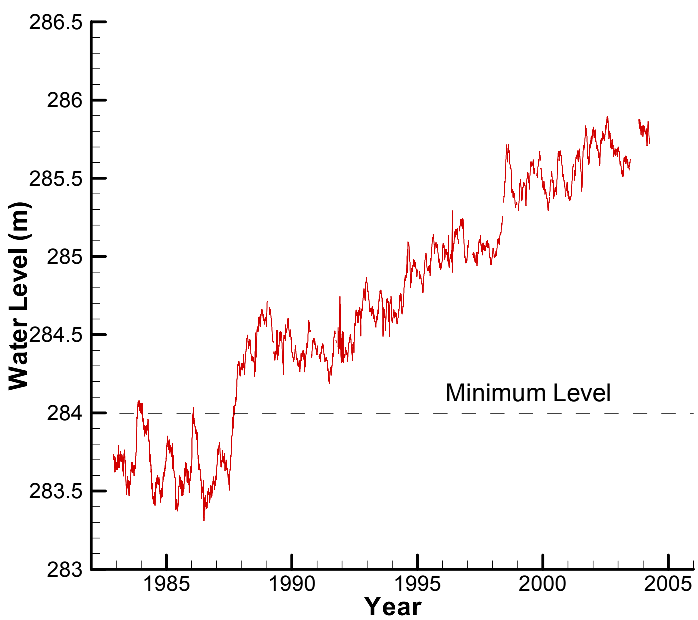

Figure 3.5 Water level in M12 with barometric pressure removed (from Kissling, 2005). Minimum level is the level defined in the Field Management Plan.

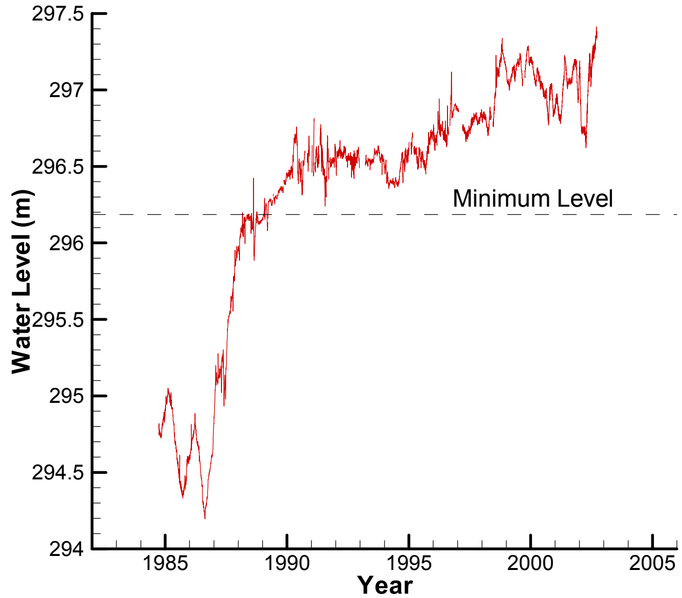

Figure 3.6 Water level in M16 with barometric pressure removed (from Kissling, 2005).

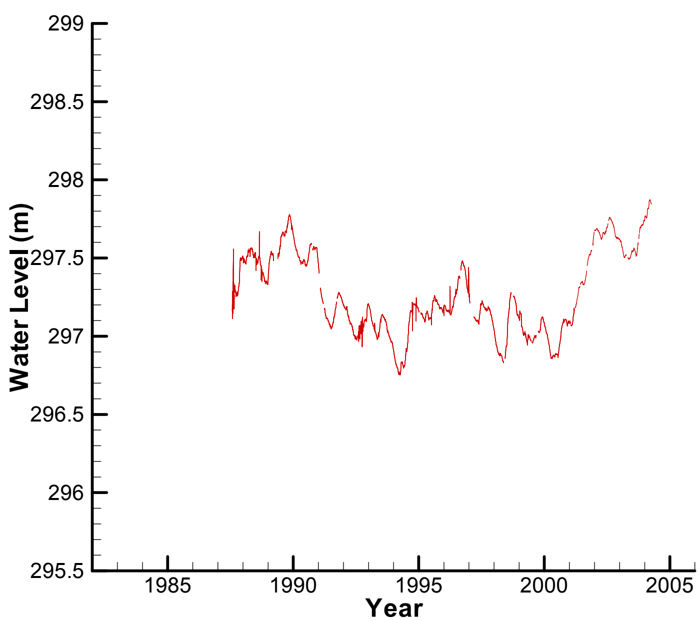

Figure 3.7 Water level in M17 with barometric pressure removed (from Kissling, 2005). Minimum level is the level defined in the Field Management Plan.

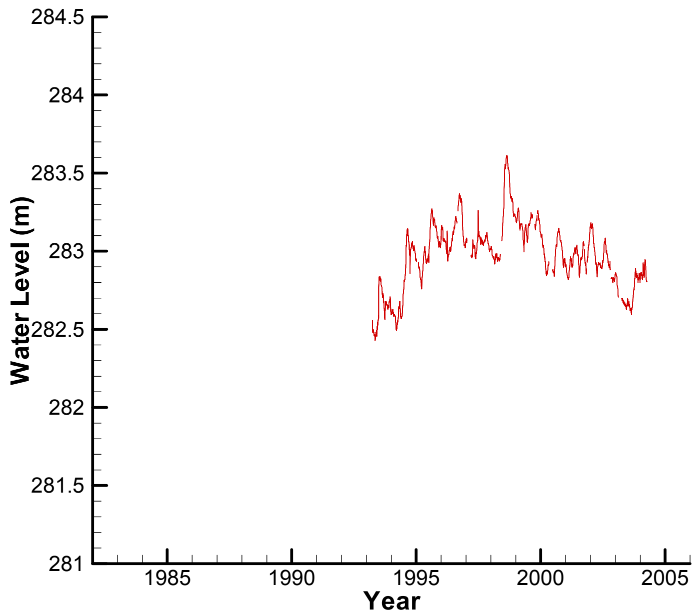

Figure 3.8 Water level in M24 with barometric pressure removed (from Kissling, 2005)

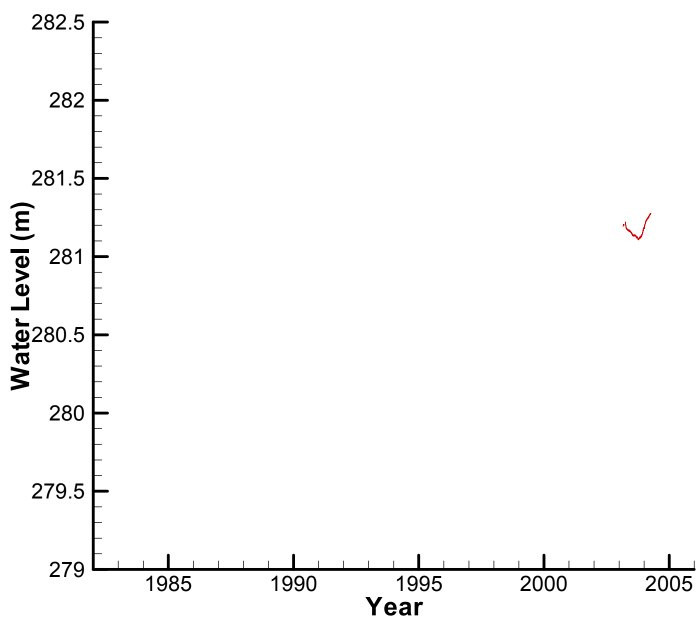

Figure 3.9 Water level in M25 with barometric pressure removed (from Kissling, 2005).

The period to mid-1986 was characterised by very strong seasonal cycles, with lows during the months of May/June (winter), and highs during the months December/January (summer). 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 cannot be seen in M1, which had only small portions of record, while the data for M9 shows an increasing annual range, which 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, M24 and M25 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 showed a consistent long-term rise in the water level (Figures 3.2-3.9). However the onset of this rise in monitoring bore M6 (Figure 3.4) 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 3.4), the rise was continuous with a slow change from 1987 to 1991, but is less than half of the increase that occurred following the bore closures. M12 (Figure 3.5) and M16 (Figure 3.6) have shown similar changes to M6 (Figure 3.3), but the magnitude of the rise in M12 (Figure 3.6) is about the same size as the 1987 to 1990 increase. Monitoring bore M16 increased from 1994 to 2000, the magnitude of this rise is about one third of the 1987-1990 increase.

For the period 2000 to 2004, there have been further changes in behaviour at the monitor bores. M1 has shown a decrease in water level of about 0.5 m, reversing the trend, which began in the late 1980s. A similar decrease, although of smaller size, is seen in M24, near to Whakarewarewa. M12 has continued its pressure rise with the total increase now being approximately twice that seen following the bore closures. At present there is no satisfactory explanation for this behaviour. M17 has shown a marked increase in water level of about 1 m since 2000. Increases of this magnitude have not occurred previously in M17, and again this behaviour is unexplained at present. Being close to Whakarewarewa and south of the ICBF, this well could be a sensitive indicator of pressures in the southern part of the geothermal reservoir, which are relevant to the thermal activity there. Taking into account the usual annual fluctuations, M6, M9 and M16 have remained at approximately constant levels since 2000. Data for M9 was not been available since 1999 and records for M25 do not yet cover a sufficient period to be useful.

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 the annual cycles have a much smaller magnitude than previously. It is likely that the annual variation in monitor bore level prior to closure was a response to the annual variation in geothermal fluid withdrawal.

Rainfall has a significant effect on the levels in the monitor bores. Figure 3.10 and 3.11 (from Kissling, 2005), shows the yearly and monthly averages respectively for rainfall from 1979 to 2004. The dashed line in Figure 3.10 shows the long term average of 1361 mm/yr. Figure 3.11 shows the highly variable nature of the monthly rainfall. The extremes of rainfall show clearly on this Figure - there are 7 months during the period 1979-2003 where the monthly rainfall exceeds 250 mm, and 9 months where it is less than 20 mm. Figure 3.12 explores further the relationship between heavy rainfall events and water levels in the monitor bores.

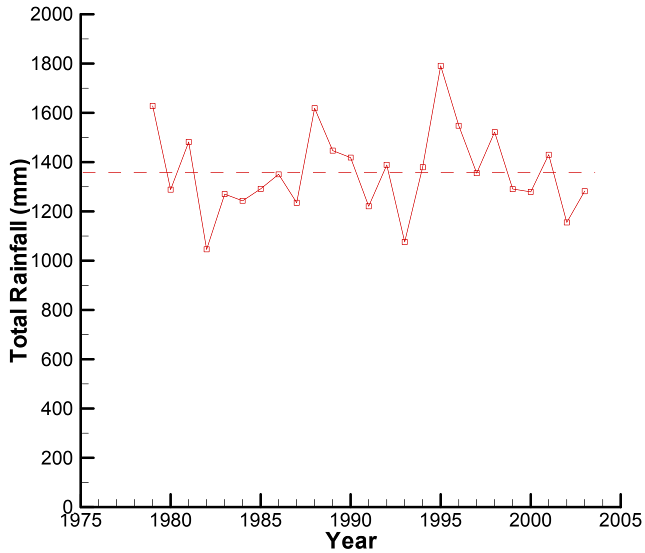

Figure 3.10 Average annual rainfall in Rotorua from 1979 to 2004 (from Kissling, 2005).

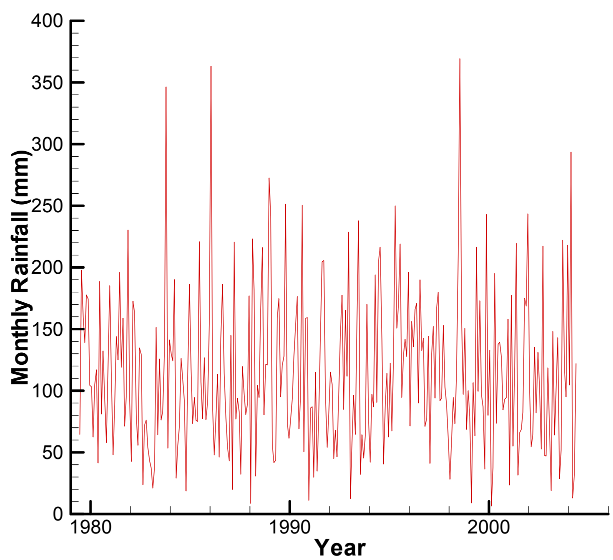

Figure 3.11 Monthly rainfall in Rotorua from 1979 to 2004 (from Kissling, 2005).

Rainfall tends to increases the level in the ground water bores, and also affects the level of Lake Rotorua, although this is controlled at Ohau channel. 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.

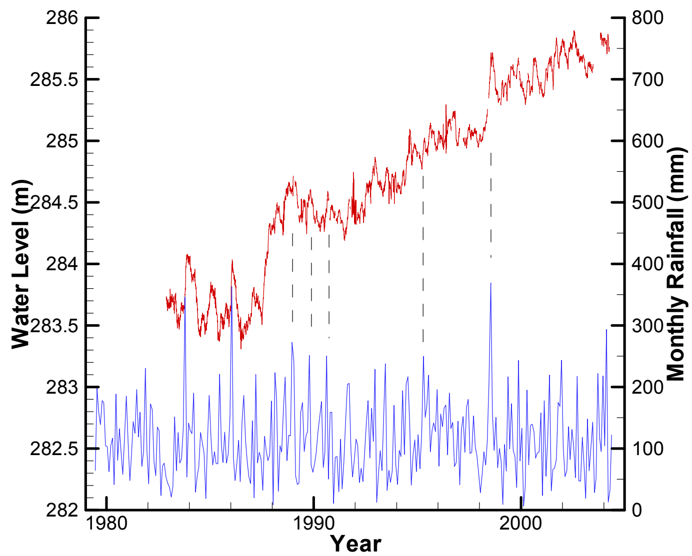

Figure 3.12 High rainfall events in the record of M12 (from Kissling, 2005).

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 3.12) 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 a period of about 2 months. Most of these high rainfall and corresponding high water level events are evident in the data record of other monitoring bores. This suggests that the geothermal aquifer responds quickly to rainfall events, and that the longer term trends in water levels have a different cause. There has been a general decline rainfall since 1995 (Figure 3.10), but this is not seen in any of the monitor well levels.

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

(a) 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. This response was not caused by variations in rainfall, since during the period 1982-1988 there was a general increase in rainfall (Figure 3.10).

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 preceding 8 years. Bradford (1990) suggested that Turner's 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 Turner's model seems to be poorly based.

(b) Closure and recovery period 1986 to 1992

Bore closures commenced in 1986 with the most of the closure occurring through 1987. Figure 3.13 shows the decrease in production through this period.

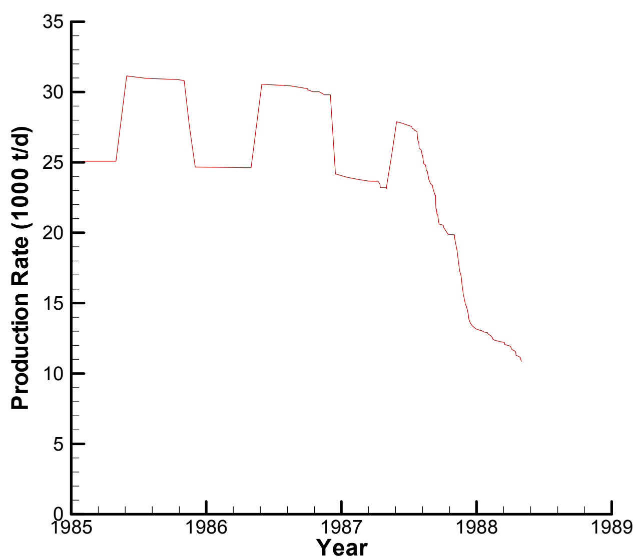

Figure 3.13 Reduction in production over the bore closure period.

Over the closure period a significant pressure increase occurred, with much larger water level changes than caused by seasonal fluctuations (Figures 3.2 to 3.9).

(c) Post-closure phase 1992 to 2004 - surface feature recovery

During the period 1992-1999 most of the monitor bores showed increasing water levels, with total level changes amounting to about 0.5 m. This cannot be accounted for by variations in rainfall, but may possibly be caused by changes in usage, which occurred subsequent to the bore closures. The exception to this is well M17, which showed variations about a nearly constant level in this period, but no long term trend.

Since 1999 however, the monitor bores have varied in their behaviour. The water level in M12 continues to increase at approximately the same rate as previously, and is now about 1.5 m above its 1992 level. There is presently no explanation for this behaviour. M1 and M24 show drops in mean level of approximately 0.5 m since 1999. For M1 this may be explained by changes in usage patterns in the Rotorua CBD, but M24, being closer to Whakarewarewa (in fact within the 1.5 km exclusion zone) is more difficult to understand. M6 and M16 have had approximately constant levels over this period. The water levels in these bores, although showing significant short time variations, are consistent with the geothermal aquifer pressures having reached equilibrium.

The rate of increase and possible onset of the slow increase in the monitor bore water levels is shown in Table 3.2. This somewhat subjective analysis shows that the onset first began in 1990 for M1 and M6, but did not occur in M16 until 5 years latter.

There appears to be no geographical dependence 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 is also unrelated to the aquifer type.

Table 3.2 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

3.3 Temperature Profiles in the Monitor Bores

Figures 3.14 to 3.21 show the temperature profiles since 1992 in the geothermal monitor bores, together with the boiling point for 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).

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 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 chemical composition. The variation in density due to temperature gives the change in height of the water column. Table 3.3 shows this rather small change for a 1ºC temperature variation.

Table 3.3 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 in water level due to a 1ºC temperature error are only about 3 to 8% of the water level change during closure, and the variation due to changes in chemical composition is rather smaller. 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.

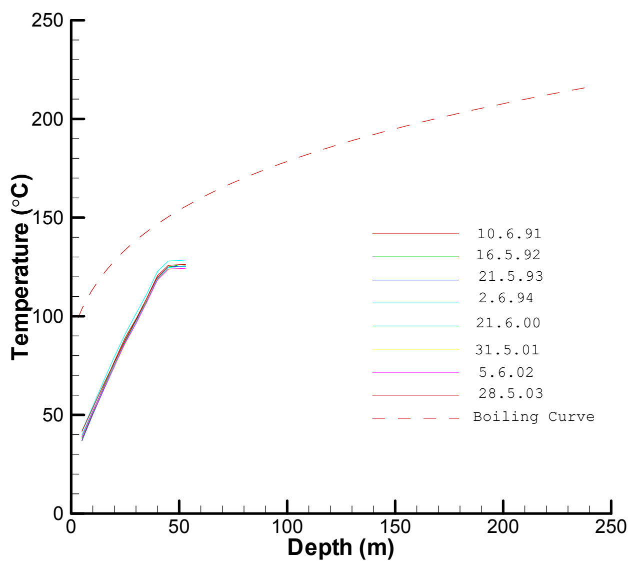

Figure 3.14 Temperature profiles for M1 (from Kissling, 2005).

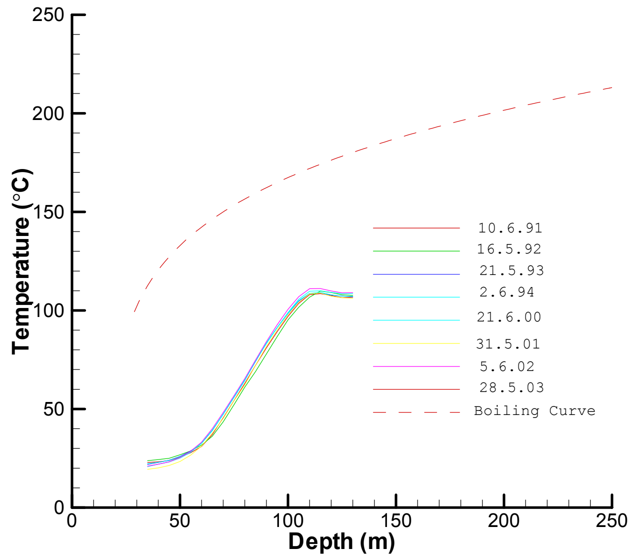

Figure 3.15 Temperature profiles for M6 (from Kissling, 2005).

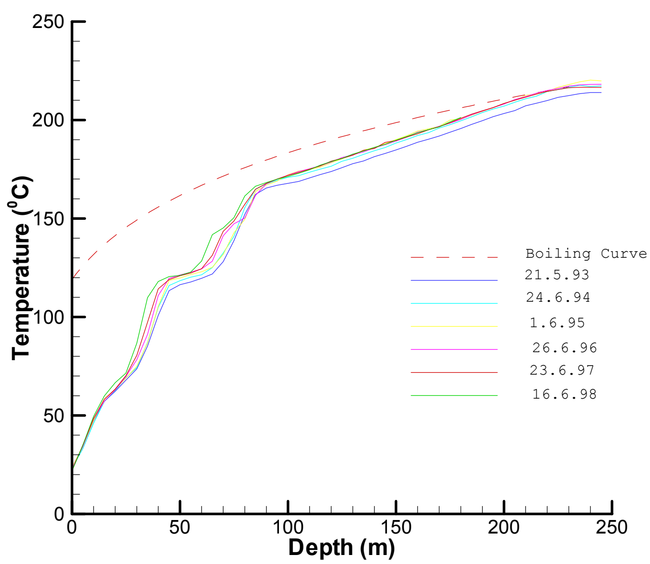

Figure 3.16 Temperature profiles for M9 (from Kissling, 2005).

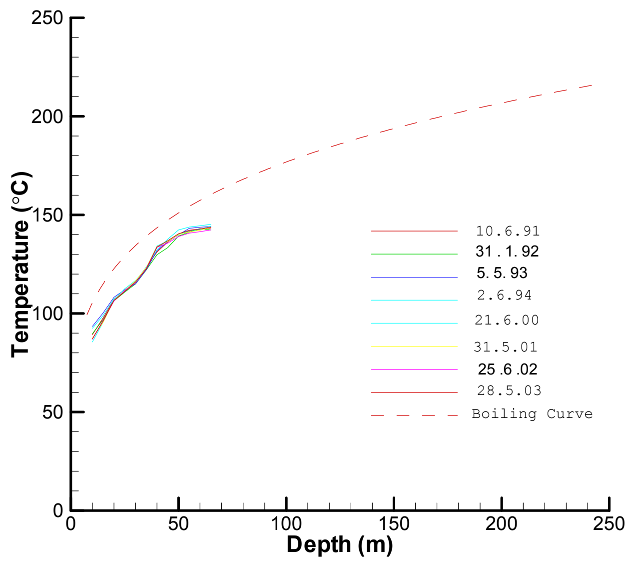

Figure 3.17 Temperature profiles for M12 (from Kissling, 2005)

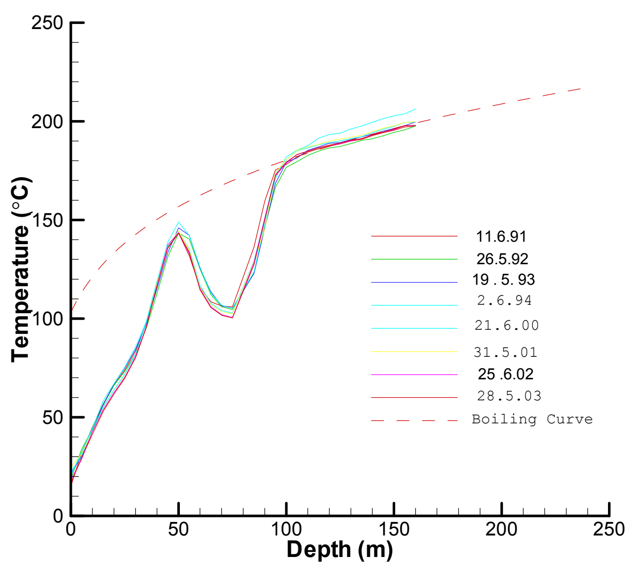

Figure 3.18 Temperature profiles for M16 (from Kissling, 2005).

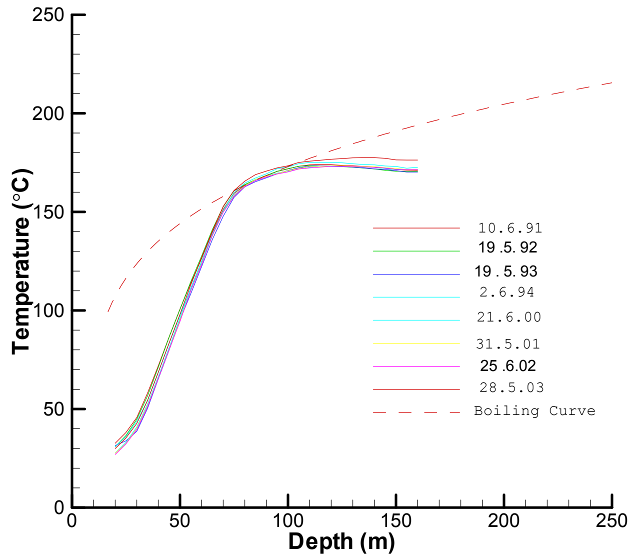

Figure 3.19 Temperature profiles for M17 (from Kissling, 2005)

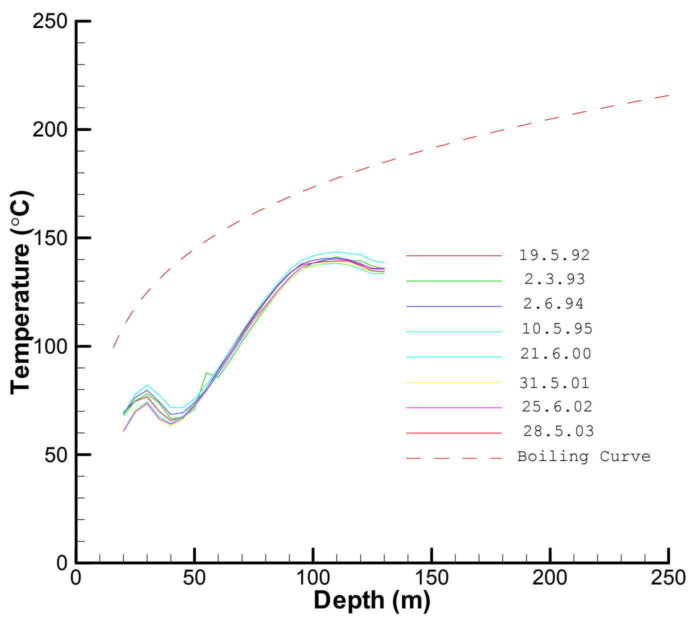

Figure 3.20 Temperature profiles for M24 (from Kissling, 2005).

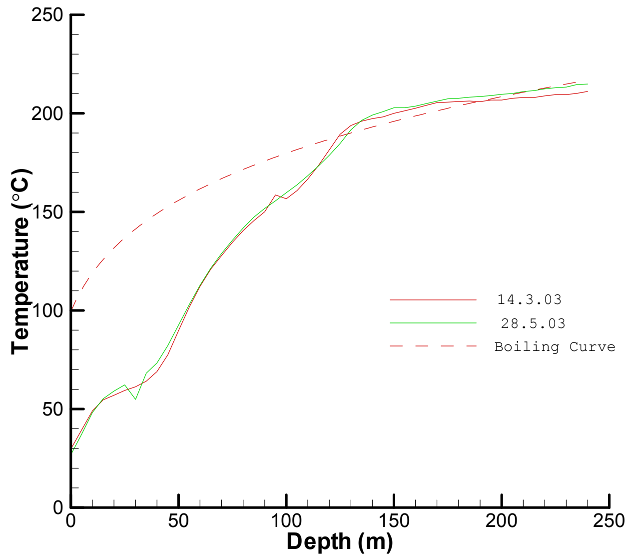

Figure 3.21 Temperature profiles for M25 (from Kissling, 2005).

3.4 Ground Water Wells

Ground water wells penetrate a cooler 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, and this resulted in a moderate component of both heat and mass contributing to the shallow groundwater. 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 rapidly 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.

Ground water levels and temperatures are recorded at approximately fortnightly intervals. Figures 3.22 to 3.31 give the historical records for water levels and temperatures in the shallow ground water wells. These are taken from Kissling (2005).

Continuous recording of water temperature data for most ground water 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) covers the period from 1983.

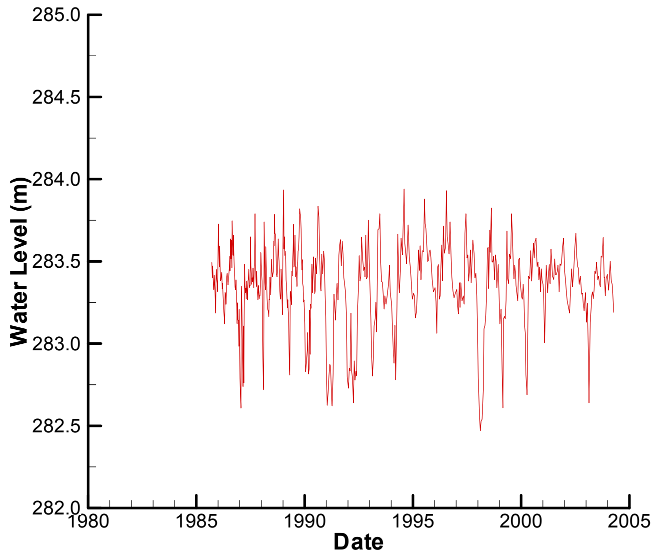

Figure 3.22 Water level in Well G2 (from Kissling, 2005).

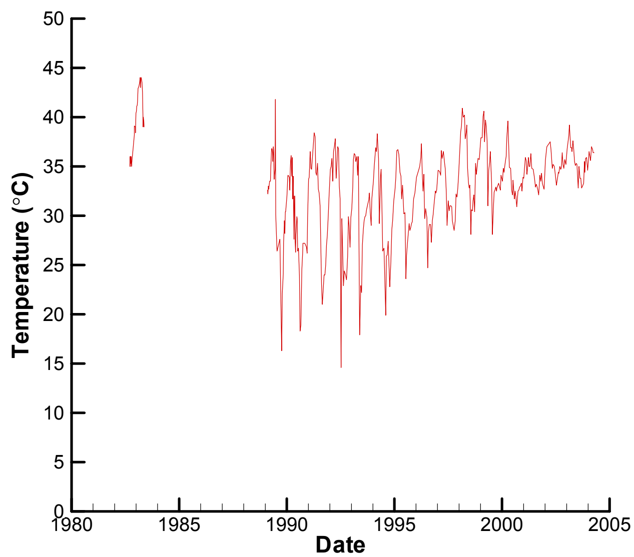

Figure 3.23 Temperature in Well G2 (from Kissling, 2005).

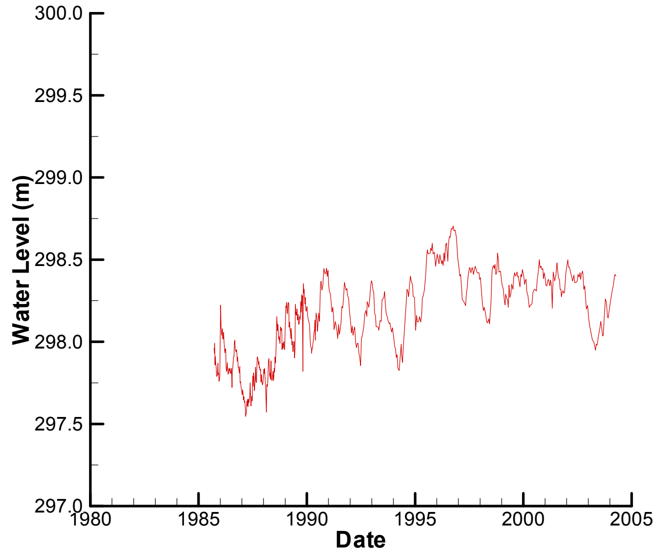

Figure 3.24 Water level in Well G11 (from Kissling, 2005).

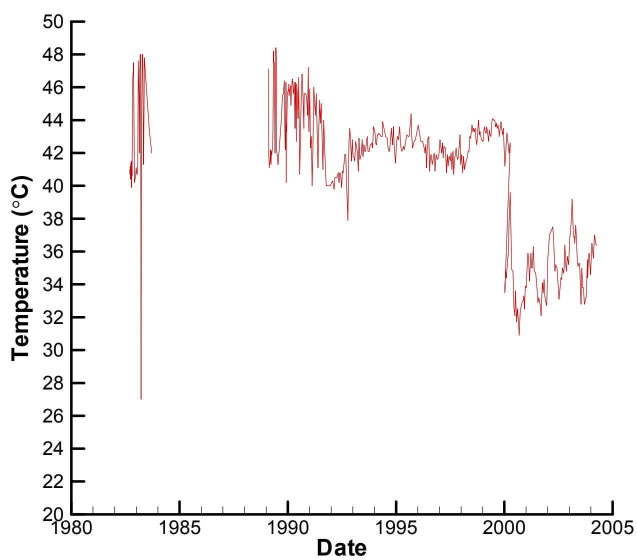

Figure 3.25 Temperature in Well G11 (from Kissling, 2005).

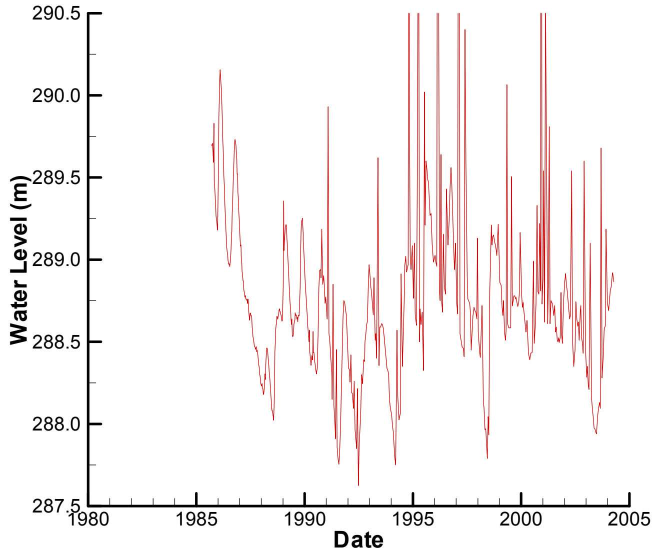

Figure 3.26 Water level in Well G12 (from Kissling, 2005).

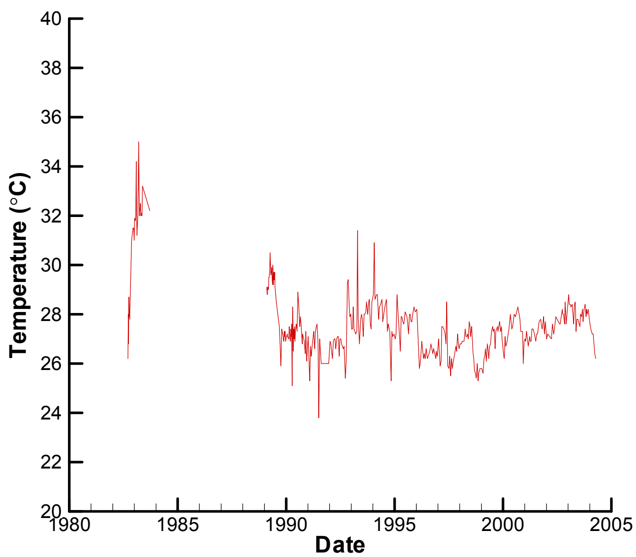

Figure 3.27 Temperature in ground water Well G12 (from Kissling, 2005).

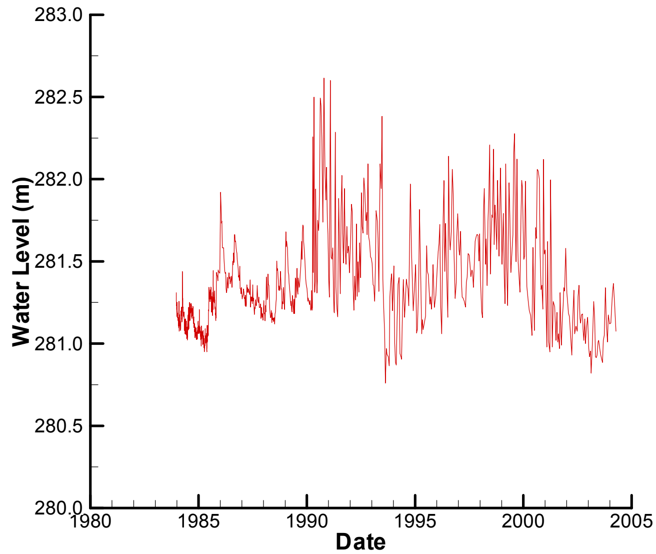

Figure 3.28 Water level in Well G13 (from Kissling, 2005).

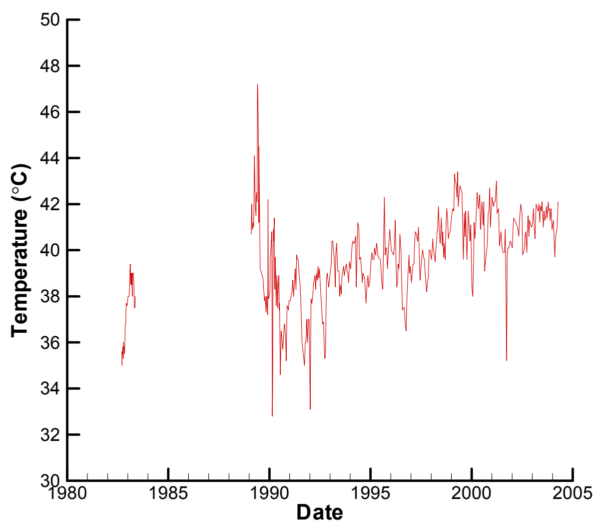

Figure 3.29 Temperature in ground water Well G13 (from Kissling, 2005).

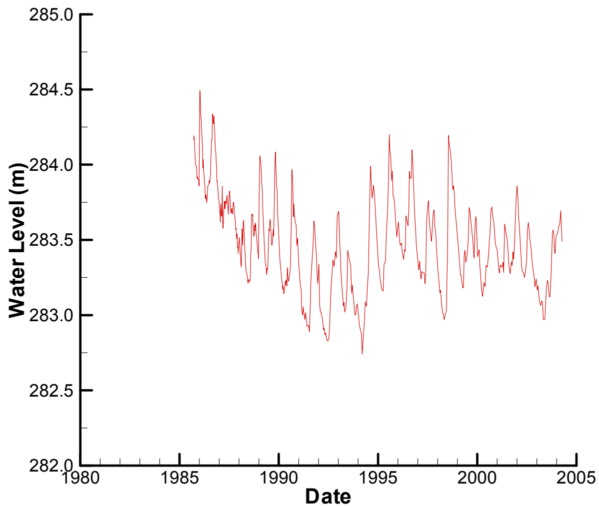

Figure 3.30 Water level in Well G14 (from Kissling, 2005).

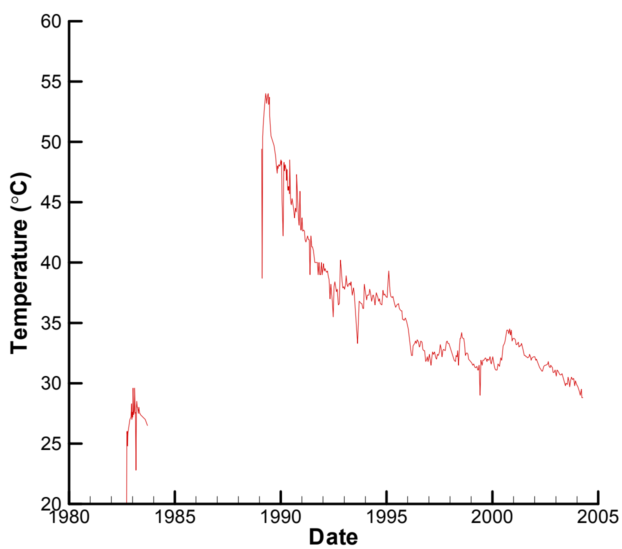

Figure 3.31 Temperature in ground water Well G14 (from Kissling, 2005).

3.4.1 Monitoring Bore G2 (Kuirau Park)

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 water level has been relatively stable since 1985. Since at least 1993, peaks have clearly occurred in the winter months, although the appearance of (early) summer peaks in 2001 and 2003 mask this annual cycle. These summer peaks are caused by high rainfall in November 2001 and September 2003. The temperature variation in G2 was relatively constant until about 1995, and then decreased slowly until 1997 when the maximum temperature rose abruptly by nearly 5ºC. During this time the minimum annual temperature increased by about 15ºC. The annual pattern of temperature now appears to be stable. It may be significant that changes in the behaviour of G2 occurred at the same time as the first evidence of changes in Kuirau Pool and Tarewa Road. Early data suggest this well was hotter (about 40ºC) in 1983.

3.4.2 Monitoring Bore G11 (Roto-a-Tamaheke)

Monitoring bore G11 has shown three different types of temperature variation in the period 1989-2004. During the 1989-1992 period the average temperature was about 45ºC, with rapid, high amplitude variations about this. From 1992-2000 the mean temperature was perhaps 2ºC less, with smaller random variations. In 2000 there was a sudden decrease in temperature of approximately 10ºC, following which the well now exhibits a clear annual cycle. With summer peaks and an amplitude of roughly 4ºC, the temperature variations are probably tied to annual summer/winter temperatures. This cycle may have been masked previously due to much higher geothermal heat input. Early temperature data suggest the temperature in 1983 behaved in the same manner as during 1989-1992. The water level does not show the same variability. This is characterised by an annual cycle through the period 1985-2004, superimposed on slower long-term changes. There is no obvious relationship between the water level data and the temperatures. This bore is near Roto-a-Tamaheke, but it appears that the level in the bore is not related to flow from Roto-a-Tamaheke.

3.4.3 Monitoring Bore G12 (Arikikapakapa Golf Course)

Monitoring bore G12 is located at the southern end of Fenton Street in Arikikapakapa Golf Course and exhibits the strongest response to rainfall events of any of the ground water wells. The strong response is manifested as very large but short-lived spikes in the water level. Underlying these spikes there appears to be an irregular yearly cycle, which shows large amplitude changes up to 1 m or more. The temperature in G12 has been relatively stable since 1988, with variations of approximately 1ºC about a mean of 27ºC. The temperature in 1983 was about 5ºC warmer than the 1988-2004 mean, with the suggestion of a rapid heating event at the beginning of the data.

3.4.4 Monitoring Bore G13 (Sewage Farm)

Monitor bore G13 is located near the Rotorua District Council sewage farm and has shown a sustained period of high frequency high amplitude oscillations in water level since 1990. Prior to this annual cycles were evident, with the mean level falling to mid 1985, and again from 1986-1988. The mean water level dropped abruptly by about 0.5 m in 1993. This was followed by a steady increase in level to 1999, and subsequent further decline to 2004. The annual mean temperature declined sharply in the period 1988-1990, but steadily increased to 2000, and has been approximately constant since that time. Early temperature data indicate a temperature of 35-39ºC in 1983, a few degrees cooler than at present.

3.4.5 Monitoring Bore G14 (Racecourse)

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 of about 15ºC that occurred in the same period. A decline in water level of about 1m occurred from 1985-1994, but the water level has since been nearly constant with a winter-peaking annual cycle. However, in the most recent data, the winter water level peak of 2003 is missing, and appears instead to have occurred in the summer 2003/2004.

A temperature peak of nearly 50ºC occurred in late 1988, which was followed by a temperature fall to around 35ºC in 1996. Chemical analysis suggests that the 1988 high temperature recorded in G14 was a steam heating episode. From 1996 to 2004 the water temperature seems to have behaved less regularly, but in total has fallen a further 5ºC. Again, this is consistent with a continuing reduction in steam heating. The pre-closure temperatures were between 25ºC and 30ºC, and G14 is again approaching these levels.

3.4.6 Discussion

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 3.12), 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.

3.5 References

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Chapter 4: Surface Feature Activity

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4.1 Introduction

Geothermal features are the surface expressions of the underlying geothermal system and are produced by upflows of hot water and gases (including steam), to the surface. The Rotorua Geothermal Field (RGF) is unique in that it contains one of New Zealand's last remaining areas of major geyser activity located at Whakarewarewa (Allis and Lumb, 1992), which is recognised to be of great regional, national and international significance. The thermal activity of the field has strong social, cultural, intrinsic, and economic values to the people of Rotorua (Environment Bay of Plenty, 1999). Recent studies by Butcher, et al. (2000) estimated that the economic value geothermal activity as of tourist attraction to the Rotorua district is in the order of $310 million per year. It was also found that nearly 18% of all local employment either partially or totally dependent on tourism.

Surface geothermal activity of the RGF is generally confined to three areas: Whakarewarewa – Arikikapakapa in the south, Kuirau Park – Ohinemutu in the north and Government Gardens - Ngapuna - Sulphur Bay in the north east (Figure. 4.1). An array of different types of surface features are found 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).

Detailed accounts of surface feature activity for the RGF have been reported in the following publications; Skey (1878), Grange (1937), Marshall and Rands (1941), Crafar (1974) and Lloyd (1974; 1975), Modriniak (1944). These accounts are summarised in Gordon, et al. (2001). Recent changes in surface activity have also been reported by Scott and Cody (2000) and Scott, et al. (2005). Monitoring of surface activity is part of the field management monitoring programme. Environment Bay of Plenty has contracted consultants to carry out monitoring of surface feature activity of the field. This chapter summarises the results of this monitoring program together with historic information.

4.2 Surface Features of the Field

There is a range of surface feature activity across the 3 main geothermal areas of the RGF. Hot alkali-chloride springs are found at Kuirau Park, Ohinemutu and Ngapuna in the north and at Whakarewarewa in the south. Ongoing geyser activity is generally confined to Whakarewarewa. Acid sulphate or steam heated features are typically found at Arikikapakapa and at Ngapuna/Sulphur Bay. Following the reactivation of springs in Kuirau Park area near Tarewa Road a comprehensive database has been compiled to better identify hazard risks and aid in protection of surface features. There are now 1570 sites for RGF in the database (Figure 4.1).

Monitoring surface features is problematic because there can be a wide variability in natural activity. However, flowing hot alkali-chloride springs and geysers are generally the most frequently observed and measured, because they generally reflect the geothermal aquifer outflows and because of their well recognised importance. Hot springs and geysers are also less likely to be affected by localised changes in shallow groundwater and rainfall compared to acid/sulphate steam heated features.

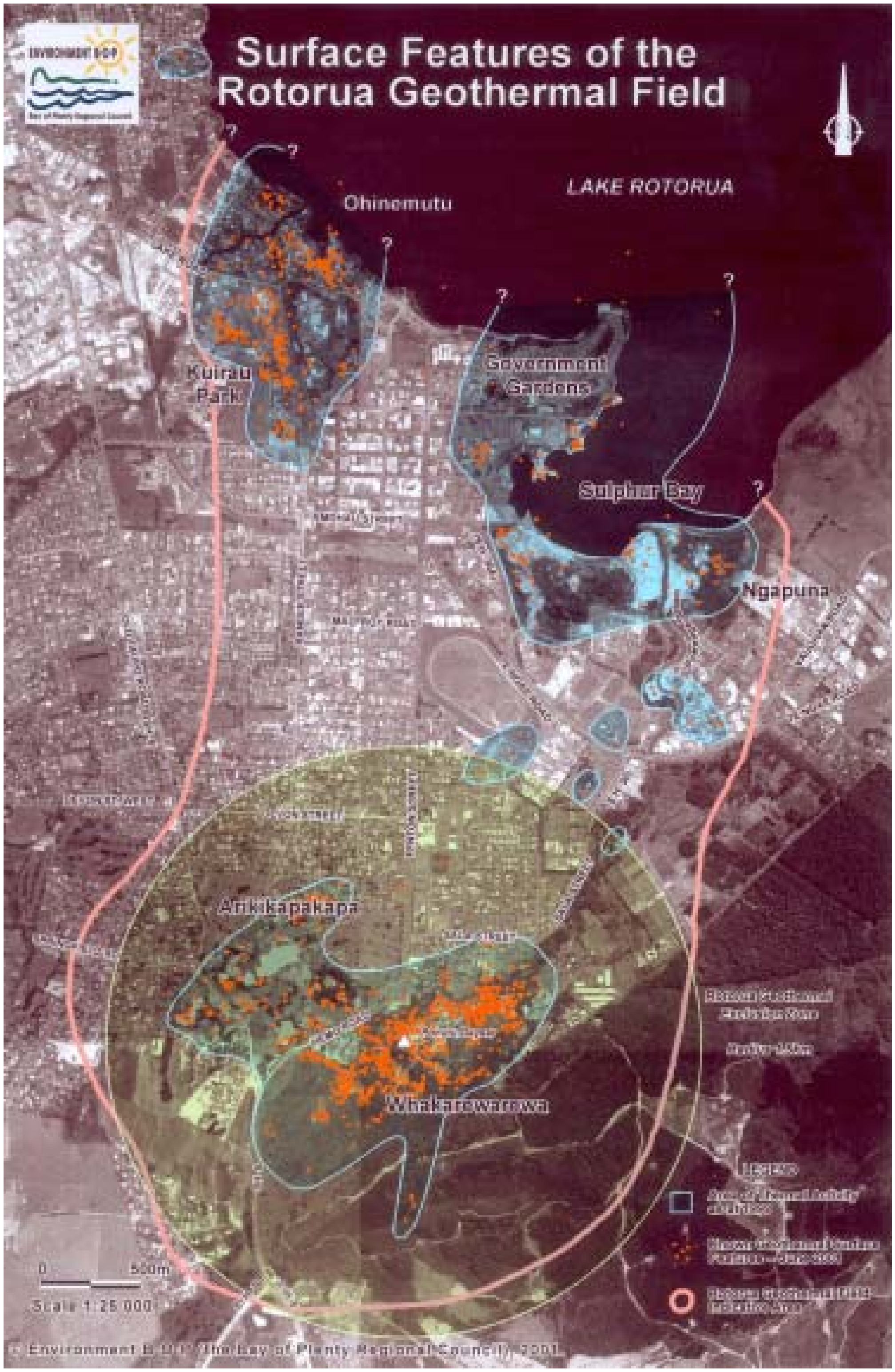

Figure 4.1 *Map showing the reported positions of individual geothermal features held in the Environment Bay of Plenty database. Areas of surface geothermal activity are outlined in blue.*

4.3 Monitoring of Surface Features

Many springs and geysers have up to 150 years intermittent record of information. However, only a limited number of springs and geysers have sufficient quantitative observations and measurements. From 1982 the government funded monitoring programme, provided a very intensive set of measurements that enabled a monitoring benchmark for when the RGF was under stress from bore drawoff. Since the implementation of the management for the field, Environment Bay of Plenty has conducted monthly inspections and measurements of about 25-30 hot springs and geysers. This work provides an ongoing record of hot spring and other thermal activity. This record provides baseline to detect changes and identify trends in thermal feature activity.

Monthly reports are produced and data is collated into computer spreadsheets. The following data collection includes: temperature, pH, conductivity, outflow rates or water levels below overflow, colour or turbidity, ebullition activity (e.g. boiling, bubbling, convecting or calm). The results of the surface features monitoring observations are presented and discussed below.

4.4 Southern Springs and Geysers

In the southern areas of the RGF (Figure 4.1), Arikikapakapa and Whakarewarewa are the two main areas of active surface features. At Arikikapakapa almost all of the surface features are acid sulphate type because there is a boiling zone beneath this area of the field (Cody and Scott, 2000). Most of the features are a product of gas and steam alteration and interactions with shallow cold groundwater. The typical features types of the Arikikapakapa area are: cool turbid acid pools, boiling mud pools and barren ground or solfatara. Whakarewarewa contains a large range of features; hot alkaline springs, acid springs and pools, mud cones, mud pools and solfatara) and this area has the only active geysers. Summaries of surface feature activity Arikikapakapa and Whakarewarewa is presented below. Information and data on unusual activity or events is tabled in Appendix 1.

4.4.1 Arikikapakapa

The Arikikapakapa area has no alkaline flowing springs or sinter deposits, although a chloride upflow occurs within Lake Arikikapakapa. Prehistoric sinters outcrop on the northwest shores of Tangatarua Lake, but presently all these areas contain almost exclusively steam and gas heated geothermal features.

To the northeast side of Arikikapakapa an area of boiling ground extends into residential housing along the south side of Sophia Street. Several weakly active fumaroles and dolines (collapse craters) are present, and occasionally cause problems to these properties. Since 2001 to 2005, little variation to thermal activity in this area has occurred other than changes due to seasonal rainfall and solar heating effects. Over a two day period from 21-22 February 2004, a small weakly bubbling mud hole in Arikikapakapa golf course abruptly blew out creating a 1.5m diameter crater and mud was deposited around the crater.

4.4.2 Whakarewarewa Springs and Geysers

Whakarewarewa consists of the largest collection of surface geothermal features in Rotorua, at least 65 geyser vents are recognisable, although it is most unlikely that any more than a handful of these have been active at any one time. There are also numerous hot springs, some overflowing and others with varying water levels. There are also large areas of warm to hot ground and fumaroles. Monitoring has focused on selected hot springs and geysers. Natural changes are continually occurring which maybe due to silica deposition changing the dimensions and flow rates of conduits and channels; rupturing of flow channels and diversions or total closure of conduits by earthquake activity or the natural decay and collapse of the intensely altered ground.

4.4.3 Parekohoru and Korotiotio Springs

Parekohoru is a large circular spring vent about 8m across and is located centrally in the Rahui of Whakarewarewa Village (Figure 4.2). The historical European name for Parekohoru is the Champagne Pool, which relates to the occasional fizzy ebullition and boiling surges. This type of activity had ceased by the 1979, and over several days in July and August 1986 overflow stopped, which had not being known to have occurred before. These boiling overflow surges resumed in 1989, following the bore closures.

Throughout the 1990s, Parekohoru was typically calm (~96-97°C) and flowing (~2 l/s), but occasionally boiled and surged in a large overflow (~15-20 l/s) for a minute or less. A conspicuous feature of these boiling surges is the powerful percussive ground thumping that can be felt to ~20m from the pool. By the late 1990s and essentially to date it boils and overflows with surges of ~20 lps, every 1-2 hours.

Korotiotio (Oil Bath Spring) is approximately 30m west of Parekohoru (Figure 4.2) 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 1890s up until c.1978, when it ceased reliable surface overflows. About this time Parekohoru was then channelled to supply the Oil Baths instead. All of Korotiotio's vents weakened in late 1978 and stopped completely in 1979 on several occasions. In 1980 it ceased all surface overflows and these have never resumed.

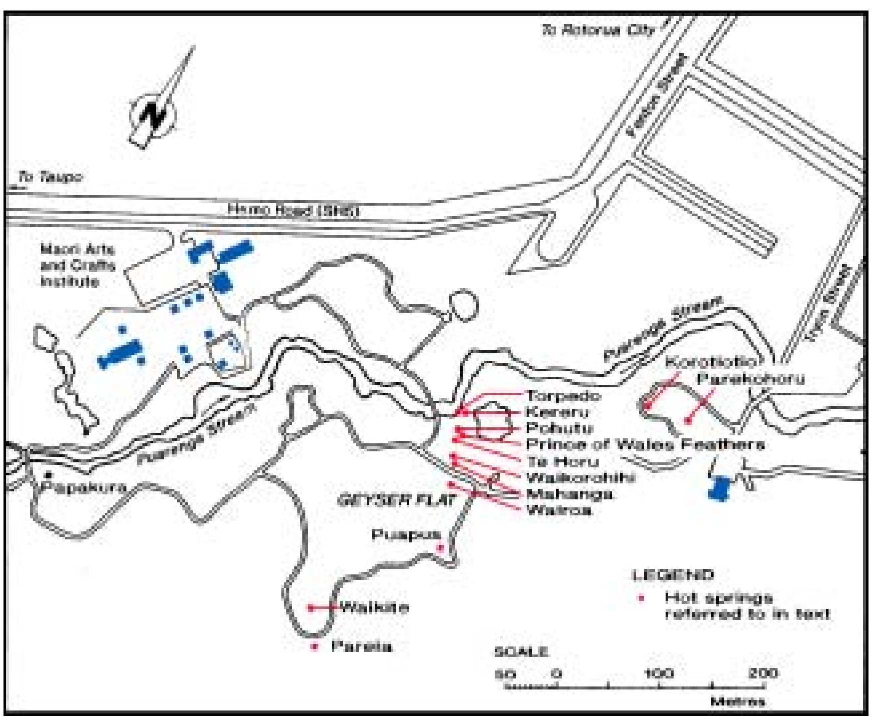

Figure 4.2 Location of major springs and geysers at Geyser Flat – Whakarewarewa thermal area.

However, during the 1970s and 1980s several hydrothermal eruptions occurred in these springs and an outflow connection to the Puarenga Stream has being established by die experiments. Hence the lack of surface overflow may not be related to any present day RGF management. Since c.1996 no further hydrothermal eruptions have occurred and its water levels have gradually risen, so that now it was usually stands at about 0.1-0.3m below surface overflow level (Figure 4.3). Boiling is now restricted to the southern most vent, from which it is typically constantly and powerfully boiling up to ~1m high.

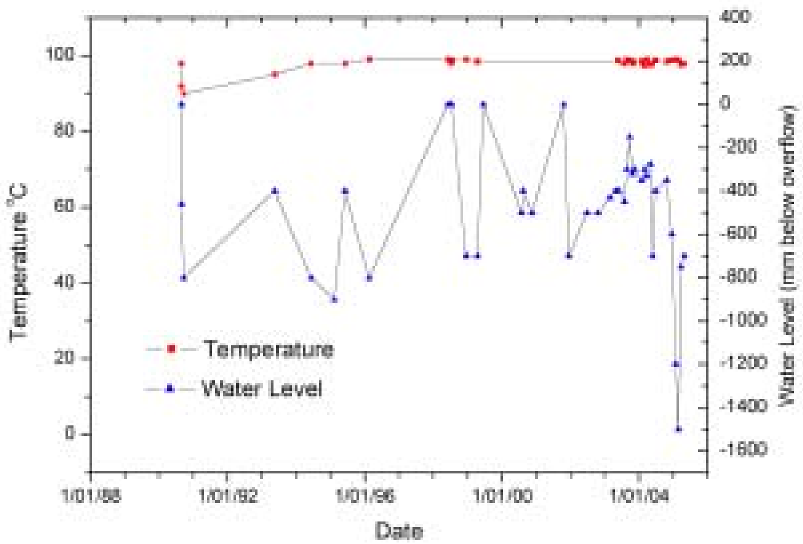

Figure 4.3 Plot of the temperature and water level in Korotiotio spring.

4.4.4 **Roto-a-Tamaheke 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 the exist around its margins (Figure 4.4). In historical times the outflows from this lake and its surrounding springs have often being altered by human intervention and the boiling of its neighbouring springs has also ceased for years at a time. Physical and legal battles contesting the diversions of water outflows were manifest in the 1890s and again in the 1930s and 1940s.

In the late 1940's boiling and overflows resumed in this area, until 1982 when many of the springs ceased overflowing. From 1982 to 1996 these springs resumed boiling overflow 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 4.5) ceased boiling and flowing; and in March 2001 all of the western lakeside springs (S377 area) abruptly ceased boiling and flowing (Figure 4.6). By late May 2001 the Hirere Bath (or Down Bath) could only be filled once a day, instead of being constantly replenished with hot water. In June 2001 many pools around the northern and western margins of Roto-a-Tamaheke had fallen to 1.2-2m below overflow and cooled, with no outflow at the eastern outlet nearby Forest Research Institute and with no boiling around the entire lake. This change is unprecedented since 1981 and is similar to the widespread collapse of boiling and flowing around here during 1938-1945. The cause of this is as yet unknown but it is contrary to the general field wide trend of improving spring flows.

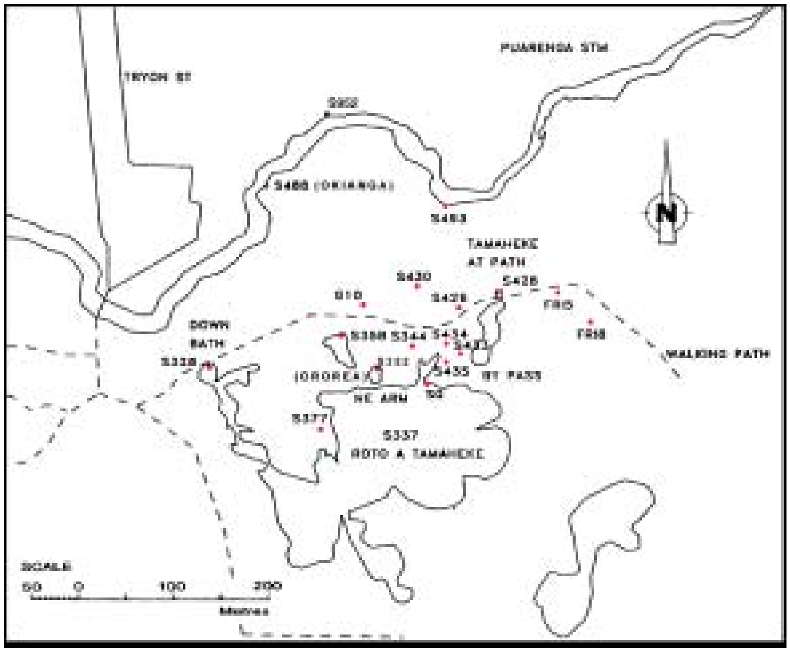

Figure 4.4 Location of major springs in the Roto-a-Tamaheke thermal area east of Geyser Flat - Whakarewarewa.

In June 2004 heavy rainfall occurred and was observed to flood Roto-a-Tamaheke which in turn flooded and quenched hot springs around the lake. Springs S352, S351, S337/1, S435, and S346 all cooled from 85-98°C down to 22-24°C. Since then springs around the margins of Roto-a-Tamaheke have not recovered (boiling or flows). However, some water level and temperature increases have occurred in Rahopeke Arm, springs S328 and S377 (Figures 4.6 and 4.7).

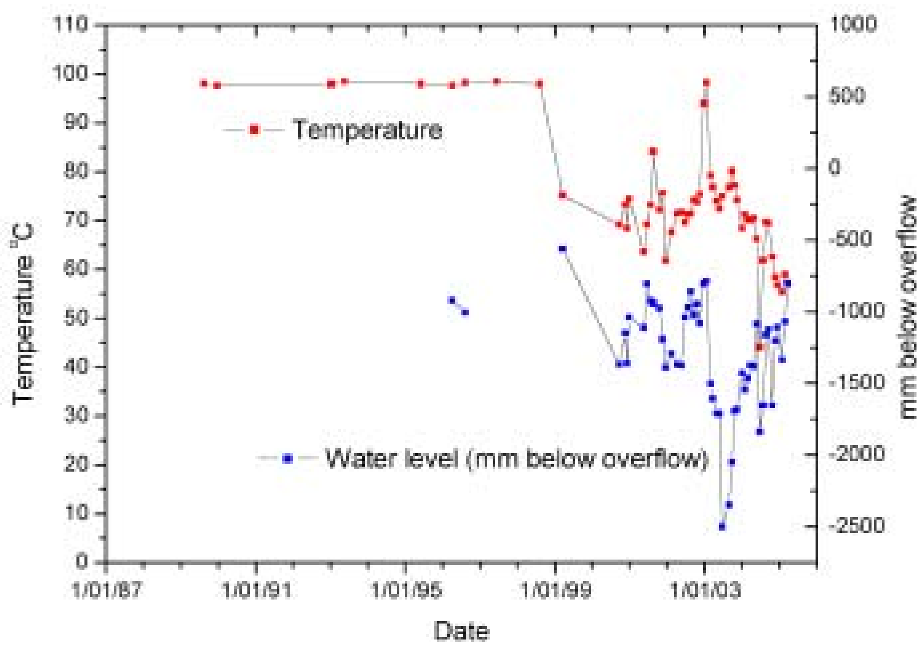

Figure 4.5 Plot of the temperature and water level in spring 351.

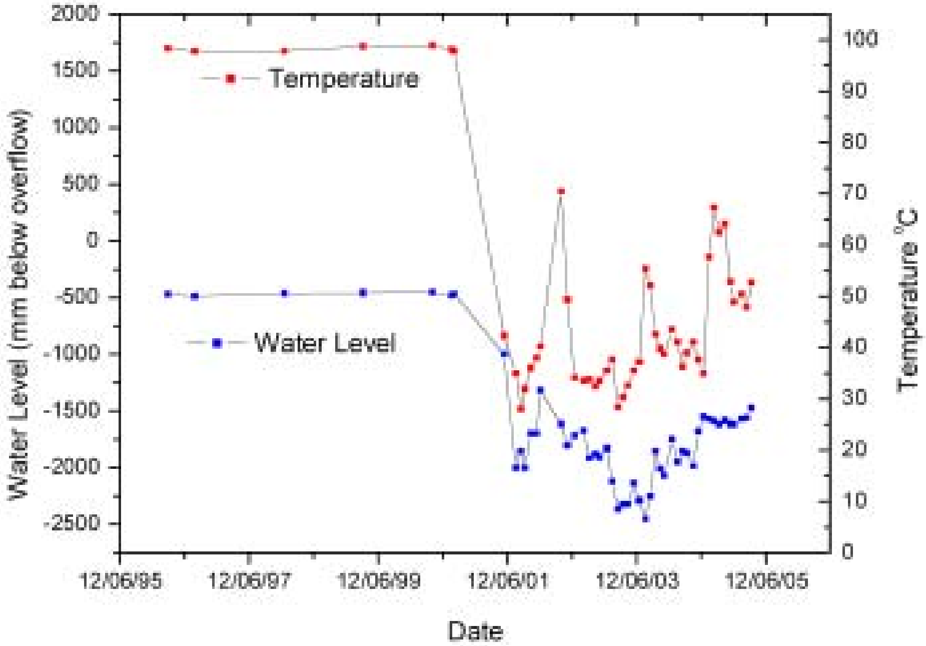

Figure 4.6 Plot of the temperature and water level in spring 377.

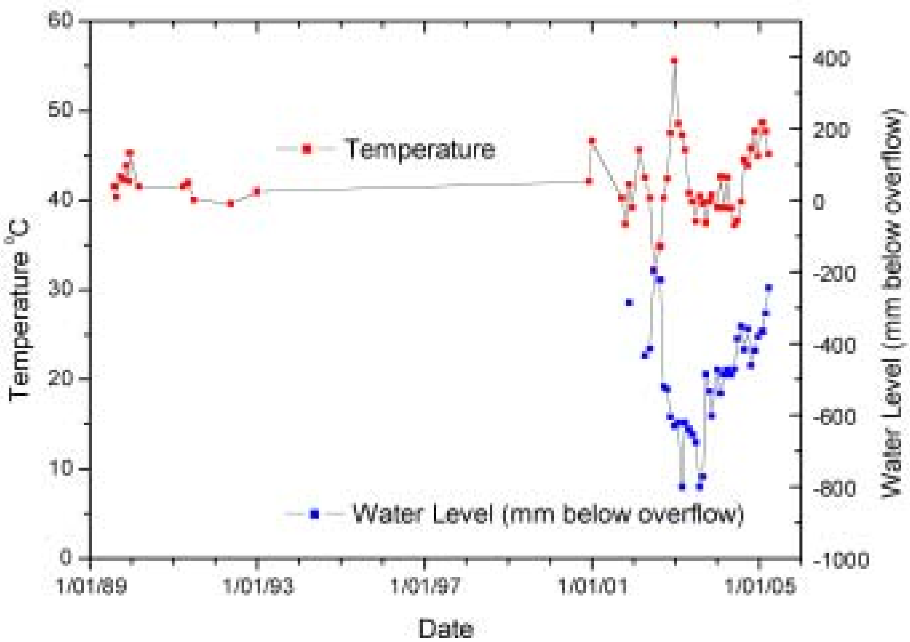

Figure 4.7 Plot of the temperature and water level in spring 328.

At the eastern end of Roto-a-Tamaheke (Figure 4.5) springs S435 and S436 geysered many times daily (3-5m high in March-April 1983), but the vents were physically damaged by human intervention in the 1980s. They resumed frequent geysering for several months in early 2004 but then became cool once more. Spring S428 has been routinely monitored in this area. Data from this spring also reflects the 2001 temperature and flow decreases (Figure 4.8).

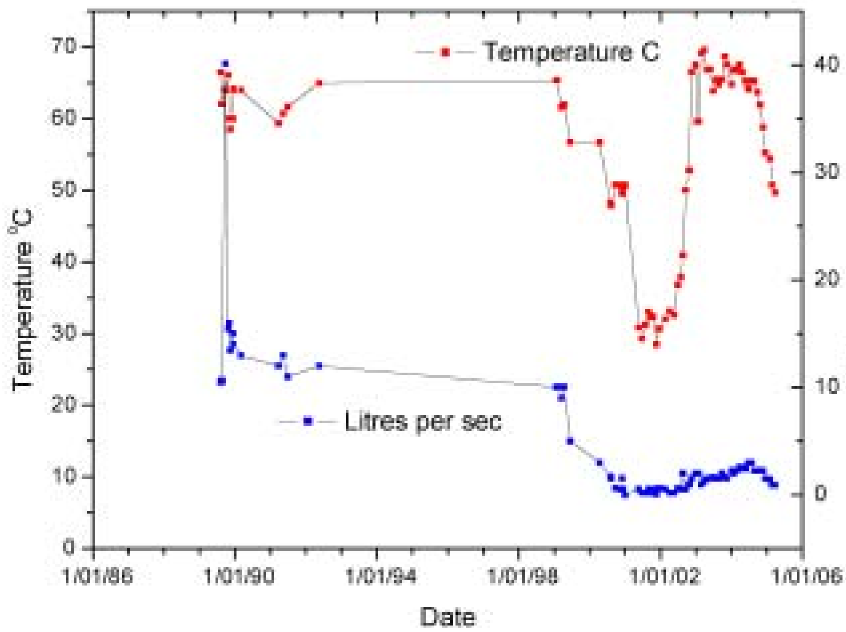

Figure 4.8 Plot of the temperature and flow from spring 428.

4.4.5 Geysers

A unique feature of Whakarewarewa is it geysers. These range from the larger like Pohutu, to the small like Okianga on the banks of the Puarenga Stream Figures 4.2 and 4.4). By definition geysers are variable in activity. Detailed below are summaries of the primary geyser features at Whakarewarewa and their recent activity.

(a) Okianga Geyser

Okianga geyser (spring S488) played ~5m high every 35-60 minutes throughout most of the late 1980s to late 1990s (Luketina, 1996; Cody, 1998). In the early 1980s it rarely erupted, but eruptive episodes tended to occur during lower air pressures. By 1999 the ground surrounding it had opened several small fissures, and several flowing vents developed, and no geysering activity occurred. Okianga Geyser began erupting again in August 2004, the first since 1999. Since late 2004 Okianga has resumed frequent daily eruptions. (Figure 4.9)

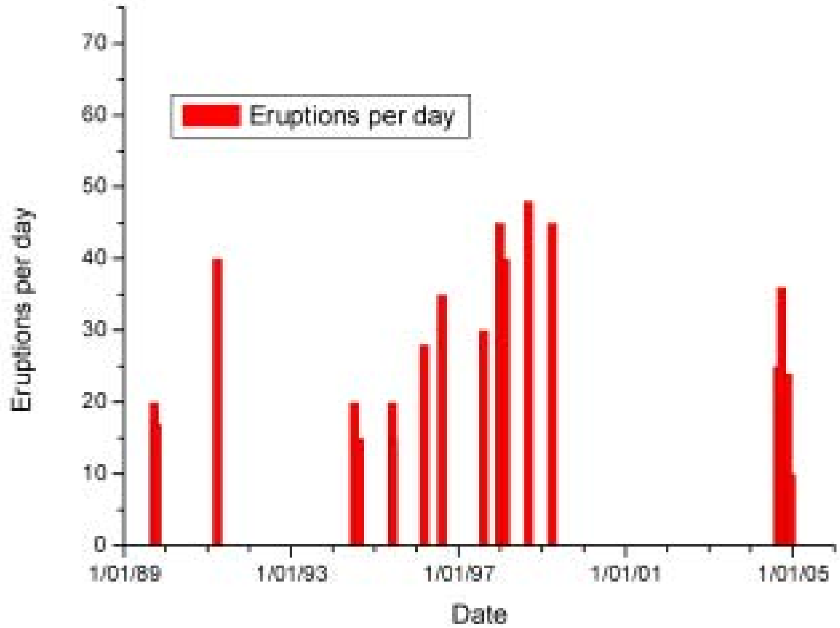

Figure 4.9 Time series plot of the number of eruptions per day from Okianga geyser.

(b) **Pohutu Geyser**

Activity of Pohutu geyser continues to change through time. Activity since 1845 to 2000 is summarised in Gordon et al (2001), see Figure 4.10.

Since late 2001 Pohutu has progressively developed longer full column eruptions that typically then collapse in to weaker splashing eruptions, then revert to steady full column plays after 10-30 minutes. True dormancies are rare. In 2004-05 Pohutu activity ranged from 2-3 dormancies each of 10-30 minutes duration, to plays for several days at a time without cessation. Because of its the infrequent and short-lived dormancies together with it being observed much of each day by staff and guides at Te Puia, it has not been instrumentally recorded for several years.

(c) **Prince of Wales Feathers Geysers**

Prince of Wales Feathers (PWF) geyser is located 2.5 m north of Pohutu geyser, at the edge of a prominent sinter mound enclosing both PWF and Pohutu. Aspects of it historic activity are summarised in Gordon et al (2001) and Scott et al (2005) and shown in Figure 4.10.

In 1992 the sinter terraces surrounding PWF became white instead of their previously orange and brown due to algal growths. This change coincided with PWF changing to nearly continuous eruptions lasting >95% of each day, whereas before then it had only played <75% of each day in many discrete eruptions. The increased outflows of hot water killed off the algal growths, which do not tolerate continuous temperatures above 60^{o}C.

Since 1992 PWF has maintained a high number of eruptions per day. It too also played nearly continuously through March 2000 to April 2001 while Pohutu was in constant eruption. However since April 2001 PWF too has also developed discrete eruptions cycles generally accompanying those of Pohutu. It also has resumed long dormancies similar to its activity in the 1970s and 1980s.

(d) Te Horu Geyser

Te Horu is a large (~5 m diameter) open vent immediately south of Pohutu and until c.1972 was a true geyser, with 10-15 eruptions every day accompanied by large overflows. Since 1972 no true geyser activity has ever been seen from Te Horu and during the 1980s water level was always below overflow, but oscillated over a c.1 hour period up to ~5m. The maximum water level height during the cyclical fluctuations was to within ~2m of overflow level.

During the late 1990s water level in Te Horu began rising progressively and in January 2000 it resumed overflows (Figure 4.10). However, these overflows have always been below boiling (<65°C) and coincident with eruptions of Pohutu when significant volumes of water flow into it.

Figure 4.10 Histograms of known activity of geysers and hot springs in the Rotorua geothermal field to 2004, after Scott et al (2005).

(e) Mahanga (Boxing Glove) Geyser

Mahanga geyser is also known as Boxing Glove, in allusion to the shape of its enclosing sinter mounds. Mahanga is located approximately 20m south of Pohutu and 4m south of Waikorohihi geyser. There is no record of activity from Mahanga until October 1961 (Lloyd, 1975), and known activity is summarised in Gordon et al (2001) and Scott et al (2005). Since 1999 Mahanga has become erratic and periods of geysering activity have progressively decreased. During 1999-2000 several days would pass without any eruptions and by 2001 eruptions had become rare, with days or weeks of inactivity. Since May 2001 no eruptions have been observed (Figure 4.11).

(f) Waikorohihi Geyser

Waikorohihi geyser has been active throughout historical times (Cody and Simpson, 1985; Cody and Lumb, 1992) and has also been observed to have unusually high (~13m) eruptions. In the 1960s and 1970s Waikorohihi typically played many times (12-20) per day, with long periods (25-45 minutes) of overflow.

During the 1980s instrumental recordings showed Waikorohihi typically erupting for 55-65% of the day with 12-15 or per day. Eruptions were generally 5-8m high with overflows of 5-10 l/s (Cody, 1986). In 1986 its behaviour changed, with many abnormally long dormancies of 3-36 hours. During the 1990s its eruption activity decreased, with fewer eruptions daily and often of short durations. From March 2000 until April 2001, no eruptions were observed at all while Pohutu was continuously erupting. Since then it has rarely erupted (Figure 4.12).

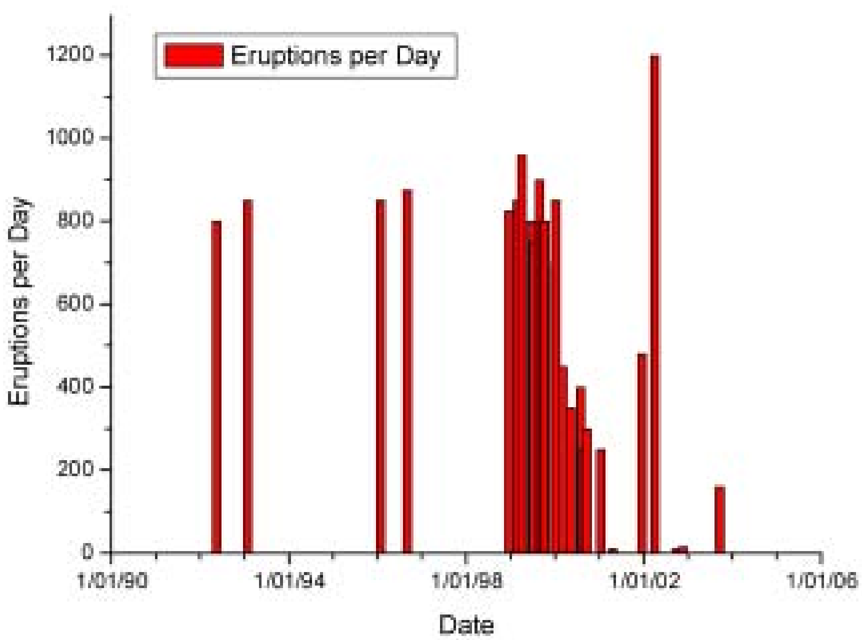

Figure 4.11 Time series plot of the number of eruptions per day from Mahanga geyser.

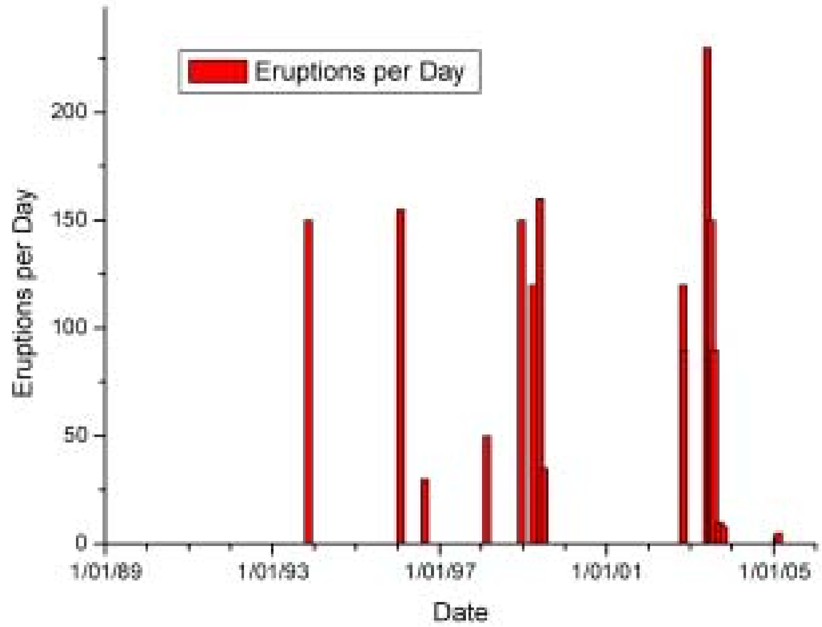

Figure 4.12 Time series plot of the number of eruptions per day from Waikorohihi geyser

(g) **Kereru Geyser**

Kereru geyser is at the northern base of Geyser Flat, on a lower terrace alongside the Puarenga Stream and activity is summarised in Gordon et al 2001. Eruptions of Kereru have no apparent relationship to any other geyser activity. From 1988 to 2000 Kereru was rarely ever seen in eruption but usually boiled continuously with splashes 1-3m high and weak overflows. However, on one occasion it was observed to erupt up to seven times in a period of <9 hours. Since 2001, it occasionally erupts and in between eruptions it typically boils with sporadic splashes (Figure 4.10).

(h) **Wairoa Geysers**

Wairoa geyser is about 15m south of Mahanga geyser. It has not erupted naturally since 10th December 1940; although many large (~40-50m high) soap induced eruptions occurred during 1958-59. In 1996 the water level rose in the vent to ~3.2m below overflow, about where it remains (Figure 4.13). In early 2005 its waters became very muddy for several months but still remained strongly acidic and boiling at 3.3 – 3.8m below overflow.

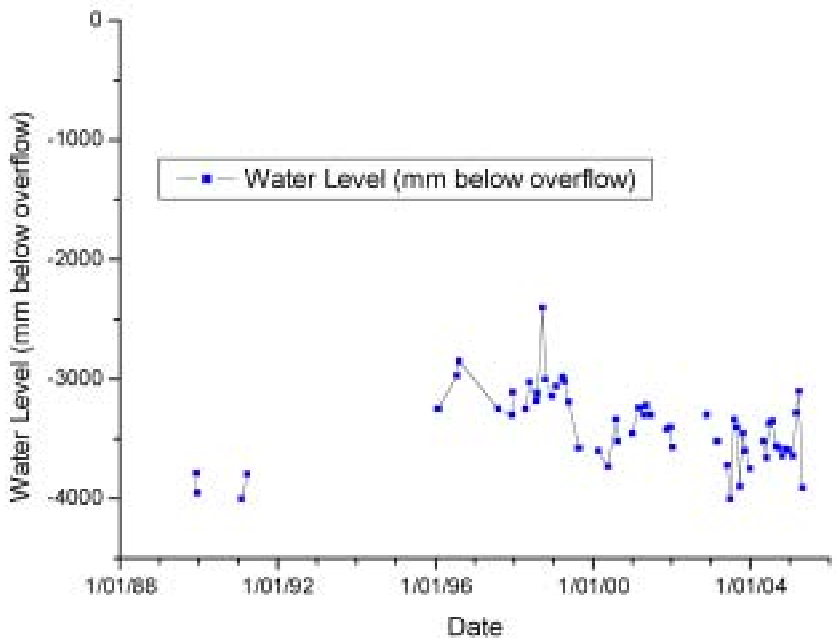

Figure 4.13 Plot of the water level in Wairoa geyser

(i) **Waikite Geyser**

Waikite is on top of a prominent sinter dome at 315m a.s.l and is the highest elevation of any spring active in the RGF during historical times. In the past its eruptions have always been very erratic and it last erupted in April 1967. Twice during the 1990s its vent has filled to within 3.2-3.5m of overflow with clear boiling waters. In November 2004, the water level in Waikite geyser had fallen to >4.65m depth, being below a rock choke at that depth. It still has powerful steady boiling but now muted and deep.

(j) **Pareia Geyser**

Pareia geyser is located on the southeast end of Waikite Mound. Through historical time it has only erupted for a few months or years at a time followed by years of inactivity. It erupted during February to May 1981, and then remained dry until a few eruptions were seen during 27-29 December 1988. It then became dry and empty once more until 1997. In August 1997 it resumed regular eruptions again and remained active for several years, typically erupting 2-4m high for about one minute, occurring at half to one hourly intervals. These ceased in 2002 and have not resumed since (Figure 4.14).

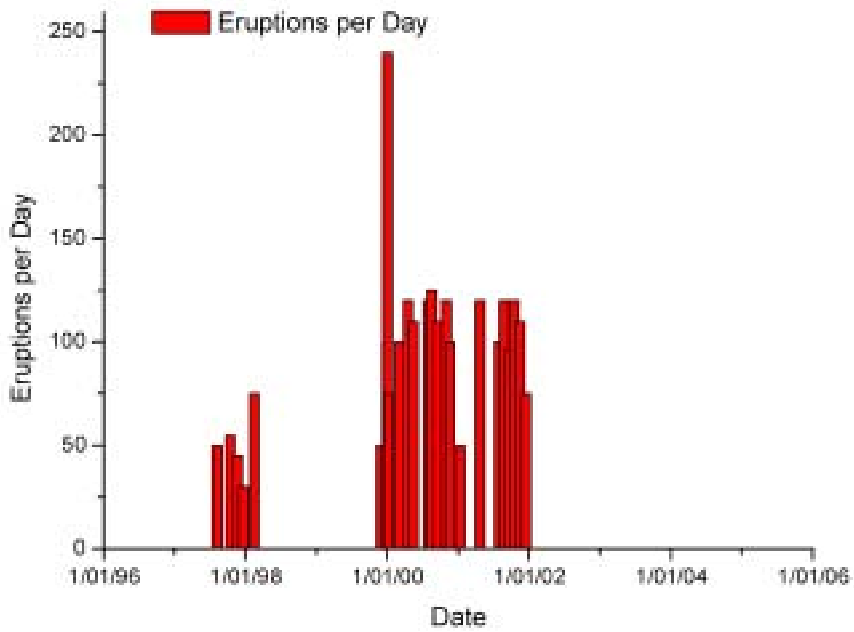

Figure 4.14 Time series plot of the number of eruptions per day from Pareia geyser.

(k) **Papakura Geyser**

This geyser is ~100m upstream of the Maori Arts And Crafts Institute. Papakura geyser was historically active until March 1979, when it ceased all boiling and geysering activity (Grant and Lloyd, 1980). During the 1990s it was characterised by a weakly acid, low chloride heated ground water pool. Since 2001 it has remained cool (35-40 °C) and a small rise in water level is apparent in recent years (Figure 4.15).

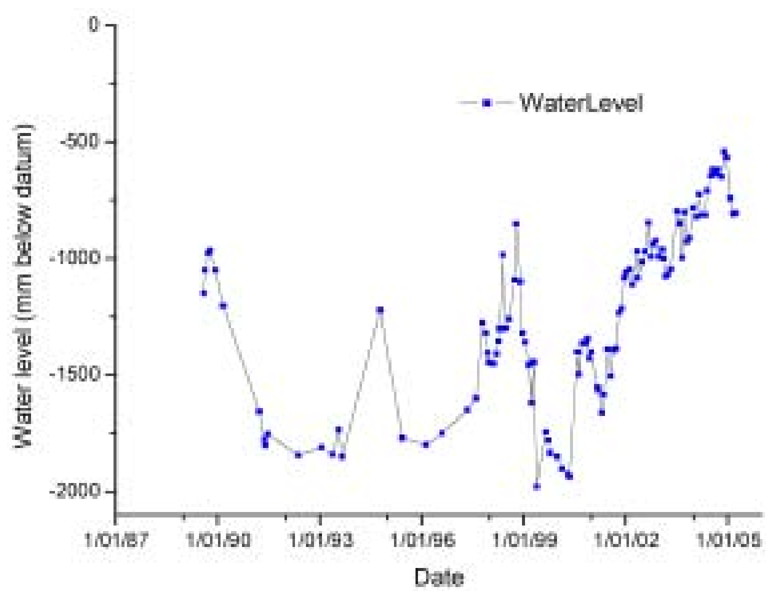

Figure 4.15 Plot of the water level in Papakura geyser.

4.4.6 Discussion

Within Whakarewarewa, there has been a wide range of changes, with apparently no consistency in the pattern of activity, either by geographic location or style of feature. Features such as Parekohoru, Pohutu, Okianga geyser, Ngararatuatara and the THC blow out show positive signs of activity, including chemical signatures reported by Mroczek et al. in Chapter 5, which indicate increased amounts of deeper fluids are reaching the surface. Whereas features such as Kereru, Korotiotio, Prince of Whales Feathers, Te Horu and Puapua appear to have not changed chemically, yet their surface activity has increased. All of the large failed geyser features (Papakura, Wairoa, Waikite and Ororea) show no signs of recovery, with acid chloride waters continuing to dominate the vents.

The surface discharges, heatflow and chemical parameters for the southern part of the field all show some signs of recovery, but there are also areas of little or no recovery. However, since early 2001 there has been a significant decline in the eastern (Roto-a-Tamaheke) area. This has not been investigated in detail, but the large loss of fluid from the Puarenga Stream in this area could be a contributor, if these fluids are mixing into the shallow geothermal fluids, but this doesn't appear to be supported by the recent chemical work.

4.5 Ngapuna and Government Gardens

Few alkali-chloride flowing springs have existed in this area in historical times, in many places geothermal waters undergo mixing with lake waters to produce turbid acidic waters.

4.5.1 Government Gardens and Sulphur Bay

Rachel (Whangapipiro) spring is the largest alkali-chloride spring in this area and has fluctuated from flowing to non-flowing, and boiling to non-boiling conditions. Since 1988 Rachel spring has rarely overflowed or boiled, its water level has fallen again to about 1.2m below overflow with little change in temperature (Figure 4.16)

Oruawhata spring, later known as Malfroy's Geyser, has boiling alkaline waters at ~2m depth, but no surface outflows have occurred since the late 1950s. In the 1990s boiling occurred at 1-2m depths. In May 2005 a ground collapse occurred to old concrete works creating a central hole ~5m diameter. Water level has established at ~1.8m depth and episodes of powerful boiling have been observed.

At the southern end of Sulphur Bay, the hot spring Matuatonga (about the site of the old Postmaster Bath) has varied in temperature and water levels but without overall trends. (Figure 4.17)

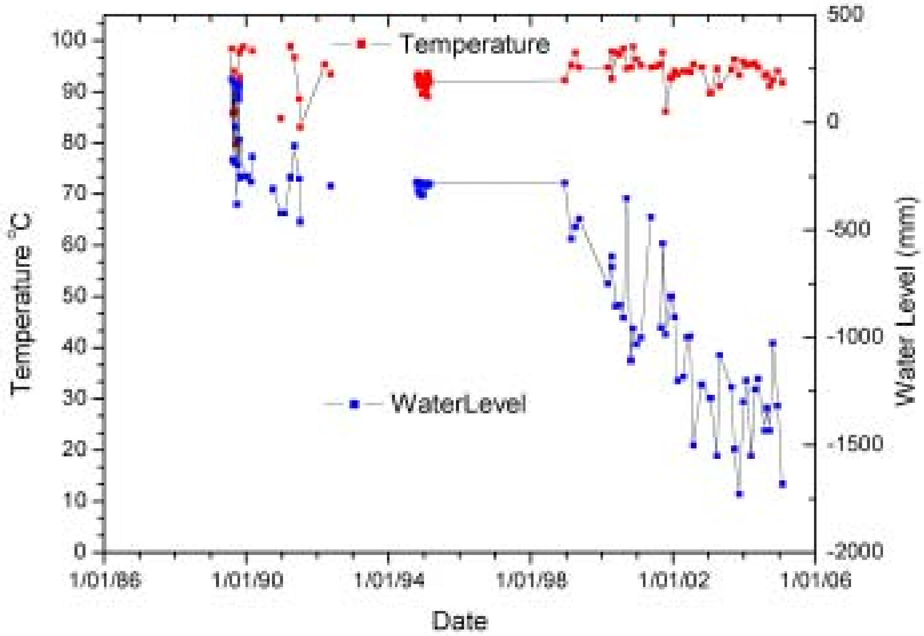

Figure 4.16 Plot of the temperature and water level in Rachel spring.

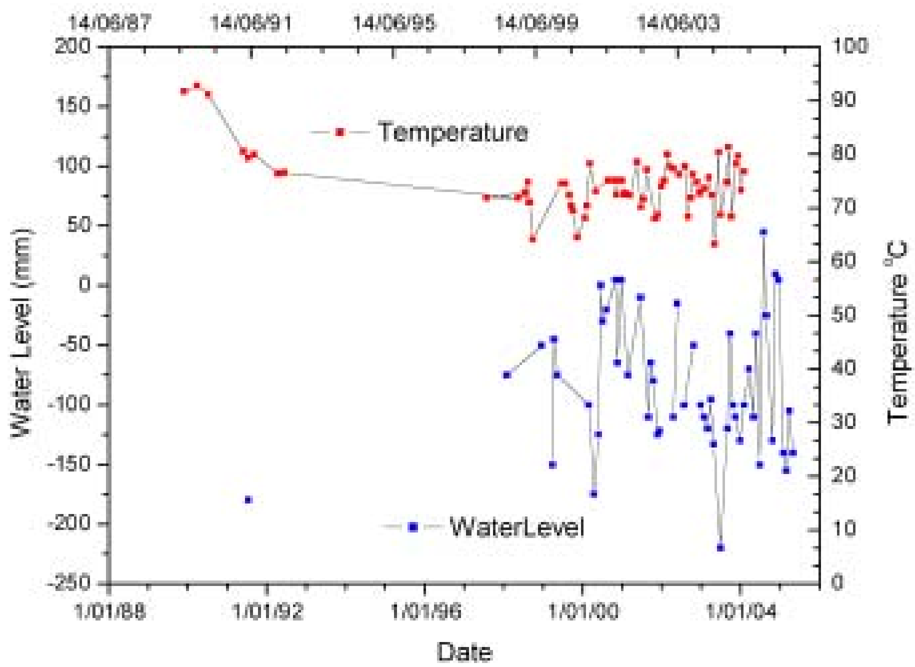

Figure 4.17 Plot of the temperature and water level in Matuatonga spring.

4.5.2 Ngapuna

Around Sulphur Bay and Ngapuna increased outflows of hot waters are noticeable but these areas have limited access so it is likely that some changes are not reported. However, monitoring confirms that the Ngapuna springs have heated and increased outflows substantially since 1987-88, with the hotter outflows having killed areas of adjoining manuka shrubs. By the late 1990s and into the early 2000's all surrounding pools have heated substantially and the waters have become clear and alkaline.

East of the Puarenga Stream, spring S940 flows strongly (~10 lps) without any changes detected through time (Figure 4.18). This feature and others are often inundated by high rainfall due to a street stormwater flowing into the area, yet they recover quickly from this dilution/cooling. Water level and temperature data from Hona Bath show little change except for a large water level fall in March 2005 (Figure 4.19). Ngapuna Bath shows variability and appears to respond to rainfall. Periodically it develops black sulphur-sulphide sediments but this is purely a variation of oxidation conditions and not contamination from any petroleum products as originally thought.

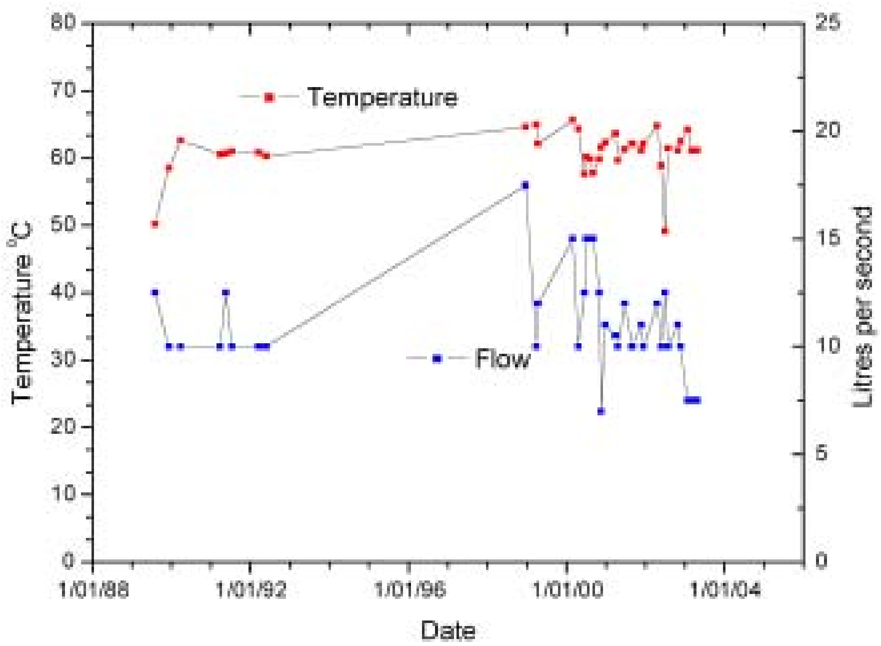

Figure 4.18 Plot of the temperature and water level in spring 940.

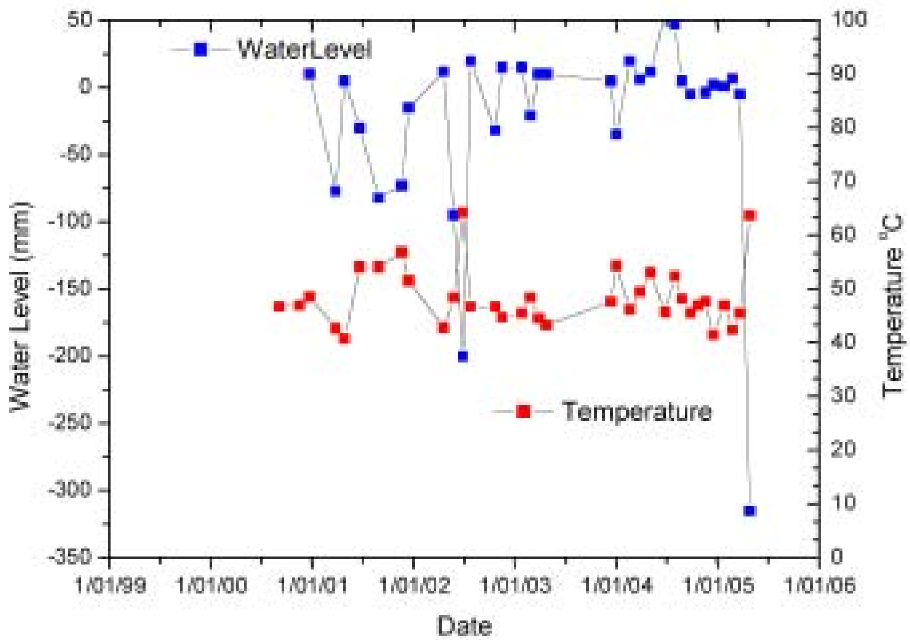

Figure 4.19 Plot of the temperature and water level in Hona bath

4.5.3 Discussion

There are few surface geothermal features in this area, however those that are monitored show trends of reheating, with increased outflows. In the Government Gardens, Rachel spring has lower water levels but the chemistry is similar in composition to that measured a decade ago. The springs in the Ngapuna area generally show increases in discharge, while the chemistry reported here suggests a decline in the portion of deep fluid, dilution and an increase in sulphate content. The Postmaster's spring (Matuatonga) and Hamiora Baths also have chemical signatures that indicate dilution and cooling, yet at the surface increased outflows are observed. A lack of sufficient temporal data may be the reason.

4.6 Kuirau Park and Ohinemutu

After a long dormancy in 1989-2001 activity at Kuirau Park became evident as hot and boiling outflows resumed (cooler and non-flowing springs). Many of the historical and post 1987 well closure changes here have been described by; Cody and Lumb (1992), Scott and Cody (1997) and also Scott and Cody (2000).

To the western side of Kuirau Park, the Tarewa Group of springs, which had ceased activity by November 1981, started to refill and resumed boiling and overflowing once again in March 1998. During the many years of dry and cold inactivity these vents became infilled with soil and debris, which progressively camouflaged the true nature of these holes. Because geothermal activity was dormant in this area through the 1940s to 1960s, building development was eventually allowed to proceed during the 1970's. As a result of these springs resuming boiling overflows once more in early 1998, four houses (Nos. 16 and 20 Tarewa Road) where affected and had to be removed or demolished. Data related to the recovery of springs in this area are plotted in Figures 4.20 and 4.21.

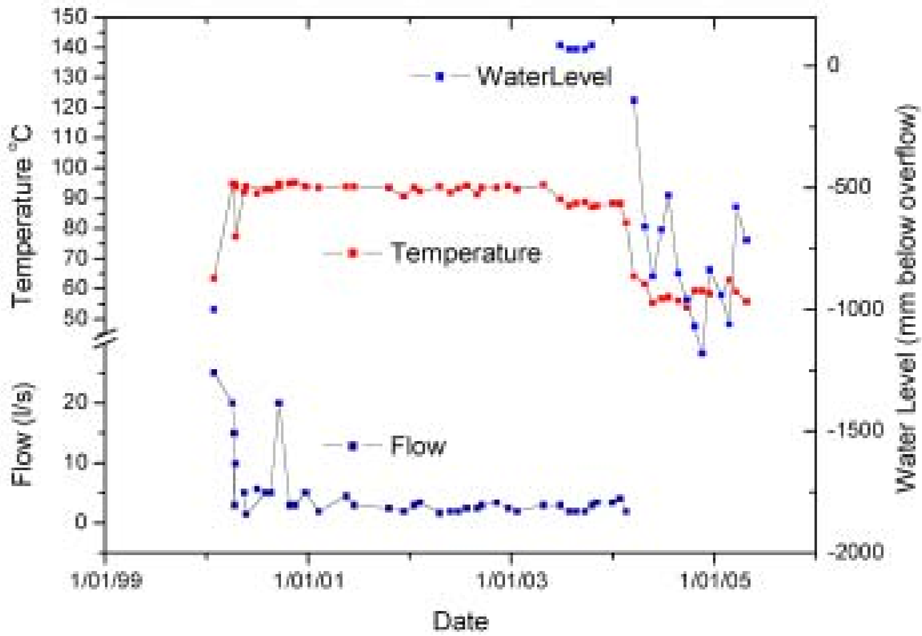

Figure 4.20 Plot of the temperature, flow and water level in spring 653.

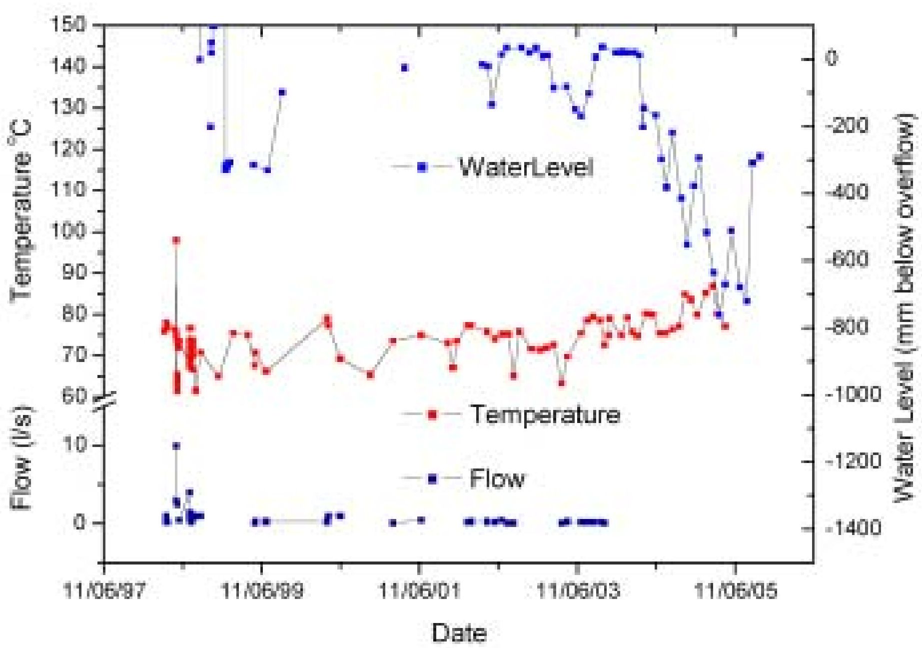

Figure 4.21 Plot of the temperature, flow and water level in spring 657.

By the late 1980s and early 1990s Kuirau Lake had resumed continuous hot (70-80 °C) and alkaline chloride outflows of 30-50 l/s. Continuously high water levels in the lake have progressively invaded surrounding shores and killed trees (Figure 4.22). However after 1991 the flows decreased.

Along the eastern side of Kuirau Park parallel to Ranolf Street, hot spring and pool water levels have increased since 1987 and this is ongoing. The Jaycee Monument and Lobster Pool (Papatangi-Waiparu) area has filled and heated and many shrubs have been killed by hot waters. By the public footbaths supplied by Soda Spring and in the area of Radium Bath, ground heating has also progressively killed shrubs and trees. Water level and temperature data from Soda Spring are presented in figure 4.23 and show aspects of its recovery.

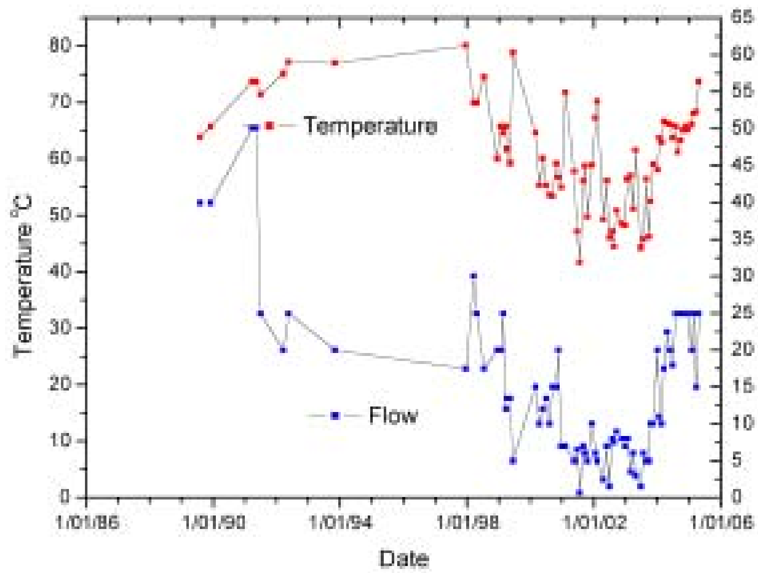

Figure 4.22 Plot of the temperature and flow from Kuirau Lake

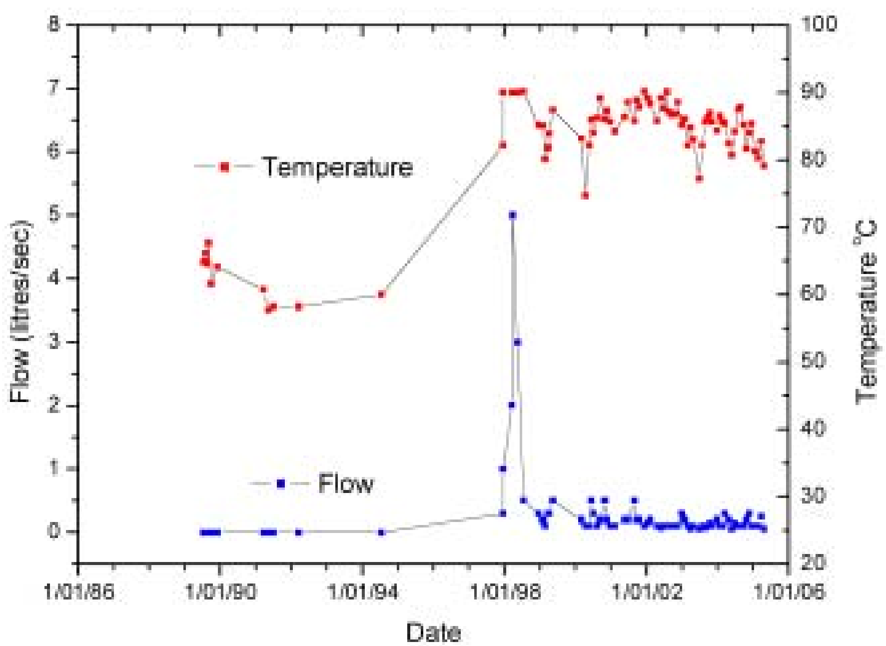

Figure 4.23 Plot of the temperature and water level in Soda spring.

The Toot and Whistle children's' playground has been fenced due to recently formed soft hot wet ground; and in the area of the old netball courts two large (~2m and ~7m diameter) hot flowing pools have formed. In June 2001 the cricket pitch again formed a collapse hole, which is now filled with warm water.

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; and an abandoned well has begun boiling and erupting alongside a residence. In Whittaker Road a home has had a hot pool begin overflowing and killing surrounding lawns.

4.6.1 Discussion

In this northern, and north-western, part of the field there has been consistent recovery of surface features. Sinter-lined basins, which were dry in the early 1980s, are now discharging fluids, which are chemically similar to those observed in the 1960s (Mroczek et al., 2002), indicating recovery to near pre-closure status. A feature of the Kuirau Park recovery has been how initially the features about Kuirau Lake first recovered, then those further to the west about Tarewa Road followed. As the Tarewa road springs recovered there was a decline about Kuirau Lake (Figures 4.20, 4.21 and 4.22). This style of change has often been documented in geothermal areas e.g. Strasser (1989) and is termed 'exchange of function'. The activity with in discrete geothermal areas changes or swaps, but the total output remains near constant. This is particularly observed in geyser basins at Yellowstone National Park (Scott-Bryan 1989). At Waimangu, 20 km south of Rotorua the activity of the two large crater lakes has been monitored for over 20 years (Scott 1994). An examination of the calorimetry and hydrothermal disturbances has also demonstrated this same exchange of function process at Waimangu (Scott 1992). It would appear similar exchange may also occur within Kuirau Park, with the flow decreasing from about Kuirau Lake as it increases at Tarewa, and vice versa (Figure 4.24).

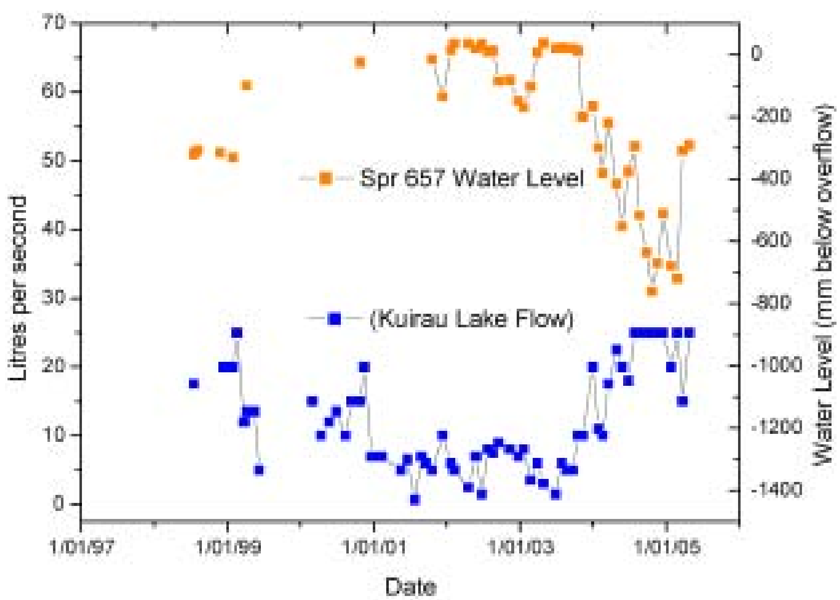

Figure 4.24 Plots of the water level in spring 657 and flow from Kuirau Lake demonstrating an apparent exchange of function between the two features.

4.7 Hydrothermal Eruptions

Rotorua Geothermal Field (RGF) has an ongoing history of sporadic ground collapses and hydrothermal eruptions (HE). This style of abrupt intermittent change is common to many NZ geothermal systems and has been the subject of various studies (Browne and Lawless 2001). Details of recent changes in the RGF are described and discussed in Gordon, et al. (2001), Cody (2003) and Scott, et al. (2005).

No detailed study of these events has yet been made, but preliminary examination by Scott and Cody (2000) suggests that periods of change or disturbances to the RGF are associated with an increased frequency of hydrothermal eruptions. In the 1970s and 1980s many such eruptions occurred throughout the RGF, however since the early 1990s the frequency of these has greatly diminished. This pattern of frequency appears to correlate with lowering RGF pressures being a time of more numerous events, with a lessened number of these events since the early 1990s from which time RGF pressures have risen by 0.3 bars or so (Cody 2003).

4.8 Events Since 2001

A number of unusual geothermal events have occurred throughout Rotorua since the summary of Gordon et al (2001). These can be separated into those involving geothermal well blowouts or leakages into surrounding subsurface ground (usually caused from failure of corroded casings) and those involving natural features. Presented in Appendix 2 is a diary of known events.

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 l00 m west of the Jaycees Fountain and Monument. The eruption lasted for about 4 minutes, reaching an estimated column height of l00 m or more and throwing out a carpet of ejected boulders and muddy rubble, which dispersed mostly in an easterly direction. Approximately 1200 m^3 of debris was ejected in this 4-minute interval, with blocks up to 1 m diameter being thrown up to 70 m away. A crater of about 15 m diameter remains, and the ejecta have been left on site as a tourist feature (Slako, 2002; Cody, 2003).

The only two other sizable eruptions were from the Ngapuna area. In May 2003 an eruption at the Ngapuna hangi area on the stream bank, blew muddy debris <50m high for several hours and a strong westerly wind spread it over houses to east >100m downwind. This is the same site that erupted on 7 March 1996. A big hydrothermal eruption was seen at mouth of the Puarenga stream on 18 January 2005, producing a column of muddy waters and rubble ~30m high, lasting for several minutes.

4.9 Bore Failures

Bore blowouts are not related to RGF resource management but as they often become notable in the public knowledge, they are included here to separate them from natural or use induced changes. In 2004 six bores had blowout failures and these events typically occur at a rate of several each year in Rotorua. Known bore failures are listed in Appendix 2. Bore casings are subject to physical and chemical corrosion and many ultimately fail, whereupon waters leak into surrounding ground. This leakage often escapes to the surface and produces a spectacular and damaging blowout of hot waters and eroded ground. These can be mistaken for natural events and are included here for completeness of the record.

4.10 Conclusions

The fundamental objective of the bore closure program in 1986 was to stop the slow progressive decline in surface geothermal activity. The monitoring program recorded a response of both the aquifer pressure and of the surface geothermal features, but it soon became apparent that the immediate response of aquifer pressure was fast, occurring over approximately two years whereas; the recovery of surface features has been a lot slower.

In the southern part of the field recovery is mixed. Several features show positive changes, increased flows and temperatures. The primary geysers are erupting for longer periods, while adjacent geysers have stopped erupting. The results of recent chemical sampling show a similar variation of positive and negative changes. Since early 2001 there has been a significant decline in the eastern (Roto-a-Tamaheke) area.

There are few surface geothermal features in the Government Gardens- Ngapuna area, however several do show trends of reheating, with increased outflows. In the Government Gardens, Rachel spring has lower water levels but the chemistry is similar in composition to that measured a decade ago. At Ngapuna the springs show increases in discharge.

In the northern and northwestern part of the RGF there has been recovery of surface features. However this has varied across the area with an apparent exchange occurring between the Kuirau springs and those at Tarewa. This has not being recognised at Rotorua before. Overall spring activity in this area has increased since the bore closures.

Geothermal systems are often characterised by disturbances, like hydrothermal eruptions, and the RGF is no different. The RGF has an ongoing history of sporadic ground collapses and hydrothermal eruptions. Since 2001 three larger events have occurred, one in Kuirau Park and two at Ngapuna.

As the bore field extraction-reinjection has being relatively steady over the last few years, with a slight increase in reinjection it can be surmised that many of the surface features are now displaying aspects of their natural variability. Across the field there has been recovery, but it is not consistent. Features which responded quickly to the bore closures have not always remained hot or flowing, while others have. Many features have been slow to show responses to the aquifer recovery as shown in the monitor bores. It is not possible to infer if this variability in the surface features is totally natural. A possible explanation for the non-recovery of some features is that hydrothermal alteration processes may have damaged the feeder conduit systems.

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Chapter 5: Chemistry of the Rotorua Geothermal Field

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5.1 Introduction

Chemical monitoring of the surface features, during the early days of exploitation and in recent times, has provided much information about the hydrology of the Rotorua Geothermal Field (RGF), and the chemistry of the hot mineralised fluids that mix with surface groundwaters, discharge at the surface, and flow into Lake Rotorua. In conjunction with physical monitoring this enables a comprehensive understanding of the current state and "health" of the field with respect to exploitation and recovery. The chemistry data also provides constraints for the complex mathematical models being developed of the field.

This chapter and Appendix A2 summarize recent geochemical studies undertaken by Geological & Nuclear Sciences in Rotorua. They are part of a continuing field management monitoring and research programme undertaken by Environment Bay of Plenty to support the objectives and polices of the resource management plan for the RGF (Rotorua Geothermal Regional Plan, 1999). A chemical and isotopic survey of selected surface features and bores was undertaken to compare the results to historical data and provide an overall assessment to highlight any changes (Mroczek et al., 2002; 2003). The survey concluded with an interpretation of existing and new survey data collected 2002-2003 to provide insight into shallow aquifer relationships between east to south (Ngapuna-Whakarewarewa) and north-western (Kuirau Park) parts of the field (Mroczek et al., 2004)

5.2 Geological Setting

The RGF is one of about a dozen large active hydrothermal systems located within the central part of the Taupo Volcanic Zone (TVZ), a region characterised by catastrophic caldera-forming Quaternary rhyolitic volcanism. The RGF, as defined by surface activity, shallow drillholes, geophysical (electrical resistivity) and geochemical surveys covers an area of 28 km2 (inclusive of the area under the lake) and occupies the southern margin of the 25 km diameter Rotorua basin, which was formed from caldera collapse associated with the eruption of the 220,000 year-old Mamaku Ignimbrite (Wilson et al., 1995).

Fluid flow within the RGF is largely constrained by geological structures (e.g. the Kuirau Fault was identified on the basis of surface thermal activity, high downhole bore temperatures, and rhyolite surface morphology), and by the properties of the subsurface formations (their natural porosity and permeability) and the thermal fluids. Wood (1992) describes the geology of the RGF, which comprises syn-caldera pyroclastic materials (Mamaku Ignimbrite), lava flows and domes (Rotorua Rhyolite), and lake sediments. Shallow drilling of geothermal bores, for abstraction of thermal fluids for heating and direct uses, has provided stratigraphic information about the shallow geology and hydrology of the area, although little is known about the geology, structure and hydrology of the geothermal system deeper than about 300m below ground level.

5.3 Previous Work

Glover (1974) compiled data for all chemical surveys undertaken in the RGF up to the mid 1970s, and provided a general outline of the field hydrology, and upflow of hot chloride-type thermal fluids near Whakarewarewa. Glover inferred that the deep thermal waters mixed with a secondary flow near the Pukeroa Dome, with both being diluted with low-chloride groundwaters as they flowed northwards. By 1985, additional information had been obtained from the field, including further chemical and isotopic analyses of the bore and spring waters, which led to recognition of the structural control on fluid flow. This led to a general model of the RGF, whereby springs at Whakarewarewa were considered to be directly fed by a 230^{o}C deep aquifer, with other upflow zones identified at Ngapuna, and lateral flows extending north and west beneath Rotorua City.

Giggenbach and Glover (1992) suggested that the main upflow zone of deep geothermal fluid at Rotorua occurred in the eastern part of the field where alkali chloride fluids are found at depth and in a few springs. A closely related plume supplied the Whakarewarewa area (characterised by slightly altered alkali-chloride, near boiling/boiling springs and geysers, which show increasing dilution by meteoric waters towards the south). A second upflow of bicarbonate-rich fluid, cooled by dilution with deeply penetrating meteoric water and altered by long contact time between water and rocks, fed bores and surface features in the northwestern part of the system. Glover (1992) indicated, from chloride budgets, that about 60% of the total output from the field discharged through the lake bottom, which implied excellent hydraulic connection between the lake floor and the geothermal aquifer.

In contrast, Stewart et al. (1992) proposed a model of the RGF, based on water/gas isotopic and chemical data, which pointed to deep aquifer fluids rising in the east, and boiling as they approached Ngapuna (where the hottest bore fluids are encountered). Waters discharging at the surface at Whakarewarewa (and Arikikapakapa, where acidic cold lakes and steaming ground are encountered, contain minor amounts of bicarbonate and were diluted by groundwater before boiling. Stewart et al. (1992) suggested that a component of this fluid flows below shallow lake sediments that underlie Rotorua City, where they are diluted with bicarbonate-chloride waters, before mixing with cool, near surface groundwater (and steam-heated fluids) and discharging in the Kuirau/Ohinemutu area.

Graham (1992) suggested a deep origin for the primary thermal waters and interaction with metasedimentary basement (greywacke) at >2 km depth, with direct upwelling in the east, plus fluid flow to the west, which undergoes dilution by old groundwater. Subsequently, Glover and Mroczek (1998) examined changes in silica chemistry and hydrological connections across the RGF, and their work pointed to two diluting fluids in the system – one at 15°C and another at 150°C, supporting the shallow mixing model of Stewart et al. (1992).

Horwell et al., (2005) mapped H_2S emissions across the RGF in 1997 and not surprisingly found high emissions along a corridor in the Mamaku Ignimbrite to the east of the Rhyolite Domes following the general NE-SW trending Ngapuna and Roto-a-tamaheke Faults. Wood (1992) speculated that these structures allowed fluids to rise from depth and considered that the northeast Mamaku Ignimbrite was closer to the main upflow than any another drilled area. Wood (1992) hypothesis that the eastern Ngapuna/Roto-a-tamaheke area of field as the main upflow was further supported by Giggenbach and Glover's (1992) geochemical evidence but is inclusive of subsequent dilution with cooler less mineralized fluids flowing laterally as proposed by other authors. Horwell et al. (2005) found significantly lower H_2S emission in the Kuirau area, which they concluded to be as result of smaller upflow in this area. This conclusion is likely to be correct but in addition to this there is also likely to be less permeability at depth in the Rhyolite, cooling and suppression of boiling of the fluid. This enables the removal of CO_2 and H_2S by water-rock reaction, resulting in "reduced degassing" in the Kuirau area.

Figure 5.1 shows a schematic representation of fluid flow paths in the RGF, which incorporate the fluid flows proposed by Giggenbach and Glover (1992), Stewart et al, (1992) and Graham (1992). This figure illustrates that there are two natural spring outflow areas of the field; (i) Ngapuna/Whakarewarewa, and (ii) Kuirau/Ohinemutu; and shows how these natural spring outflow areas of the RGF are most likely to be connected and supplied by thermal fluids at depth. Fluid rises in the eastern part of the field, which then discharges to surface features at Whakarewarewa and Ngapuna. Lateral flow to the west also takes place where shallow mixing of the fluids can occur prior to discharge. The input of deep thermal fluids and shallow mixing adds additional complexity to the outflow model for the Kuirau and Ohinemutu areas.

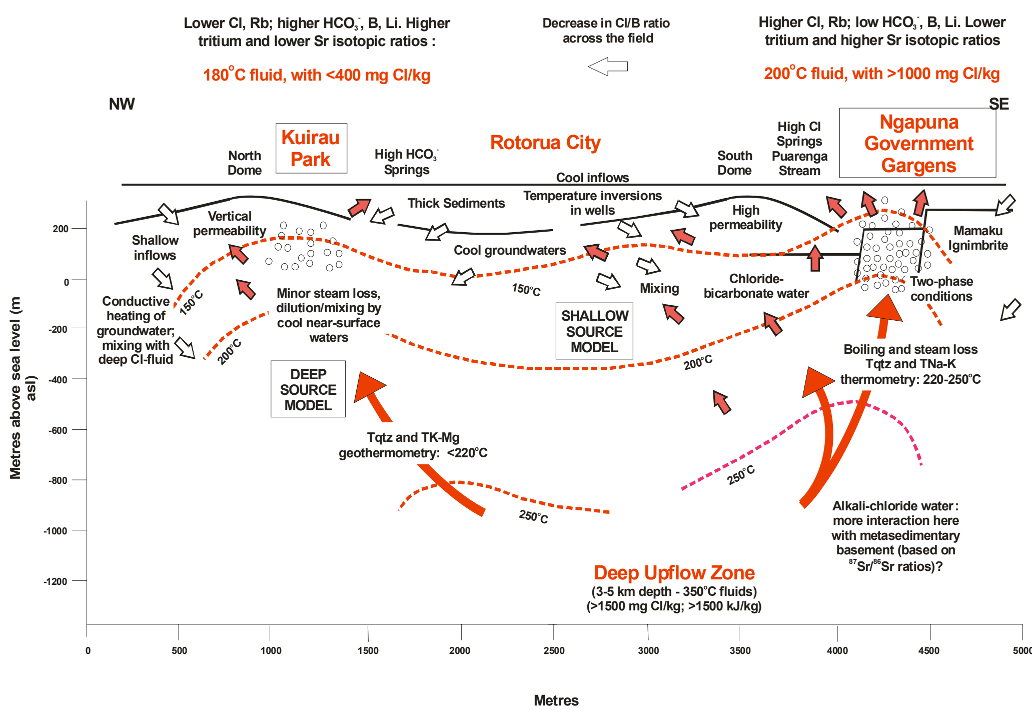


Figure 5.1 Inferred hydrology of the Rotorua Geothermal Field.

In assessing the geological implications of their results, Horwell et al. (2005) state that it is not known whether the downflows between the Rhyolite Domes discussed by Wood (1992) are a natural phenomena or if this is caused by pressure reduction as result of extensive extraction from the field. However, Wood (1992) says categorically that historical well temperature data suggests the thermal/pressure low extended to areas with low geothermal exploitation suggesting that is likely to be a natural phenomenon. Future temperature and pressure monitoring will enable the issue to be resolved.

5.4 Summary Results for Samples Collected in 2002 and 2003

Commentaries on the individual springs and bores sampled are found in Appendix 2. Tabulated geochemical data is complied in unpublished reports for Environment Bay of Plenty in Mroczek et al., (2004).

5.5 Surface Features

5.5.1 Whakarewarewa

In the Whakarewarewa area surface features show a range of chemical and isotopic changes with apparently no consistency to geographical location or spring type. These changes range from continuing decline or no recovery to stable or recovery with aquifer re-heating. These changes are discussed in detail by Mroczek et al., 2002, 2004.

In summary, the features can be grouped as:

- **Stable** – Kereru, Korotiotio (but slight increase in SO_4),
- **Declining or dominantly acid chloride fluids** - Papakura, Wairoa, Waikite Geyser, Ororea,
- **Minor recovery** - Ngawharua (increase in Cl but also SO_4), Prince of Wales Feathers, Te Horu, Puapua,
- **Significant recovery** - Parekohoru (less dilute fluids), Pohutu – substantial heating of the shallow aquifer indicated by the increases in dissolved silica and the composition (Cl and Na/K) now appears to be similar to fluids discharged in 1937,
- **Possible increase in temperature of the deeper water component** - Okianga Geyser, Ngararatuatara (small), THC Blowout (especially).

The isotope analysis indicates that Ngawharua, Korotiotio, Ororea and Ngararatuatara fluids have an increase of steam heating, whereas Prince of Wales Feathers and Pohutu geysers have a greater input of “boiled” (i.e. bicarbonate-poor) deep water. Puapua and Parekohoru springs have a greater input of “diluted” (bicarbonate-rich) deep water, and Okianga Geyser is fed by deep water, which is now more dilute. Kereru shows no change and springs S506 and THC Blowout have no previous data.

5.5.2 Ohinemutu - Kuirau Park

In the Kuirau Park area all features sampled are springs that have recommenced overflowing (i.e. recovering or recovered). It is probable that fluids types now discharging from features like the J C Fountain area, Soda Springs and Tarewa Springs are similar to the fluid that discharged in the early 1960s prior to exploitation. In the Ohinemutu area there has been little change over the last 20 years. The fluids discharged closely match those now being discharged at Kuirau Park, but the deeper aquifer fluids are cooler relative to the Kuirau aquifer.

5.5.3 Ngapuna and Government Gardens

In the Government Gardens thermal area, Rachel spring is similar in composition to that measured a decade ago. The springs in the Ngapuna area generally show a decline in the portion of deep fluid with dilution and an increase in sulphate. The isotopic compositions also indicate more dilution with steam heated water that may explain the continued decline in S940 and the Stopbank spring. The Postmaster's spring and Hamiora Baths compositions indicate dilution and cooling at depth. The springs in Ngapuna have substantially reheated (Gordon et al., 2001) with increased outflows so it is puzzling why this is not reflected in the compositions and chemistry. Lack of sufficient temporal data may be the reason and the compositions may in fact reflect a reversal in decline.

5.5.4 Bores

A chemical and isotopic survey of ten production bores over the RGF was undertaken to collect a modern data set that could be used for comparison with historical data. The choice of suitable bores to sample was severely limited due to the 1986 bore closure programme. See Mroczek et al., (2003, 2004) for more details.

The shallow aquifer feeding the bores over the last decade shows relatively minor changes in heat and reservoir chloride. This indicates stability and no deleterious processes are affecting the RGF. Geothermometer temperatures of the deeper source waters appear to have increased typically by 16^{o}C. Nevertheless three bores; two in western Rotorua and one in Government Gardens show minor decreases in silica enthalpy and reservoir chloride, which may be due to natural variability.

5.6 Interpretation of 2002 and 2003 Results and Comparison with Historical Data

5.6.1 Ngapuna – Government Gardens

Figures 5.2 and 5.3 show Cl-HCO_3 and Cl-HCO_3-SO_4 plots for samples from Ngapuna and Government Gardens. They show how the HCO_3/Cl ratios are very different for waters in these two areas; those at Ngapuna have low HCO_3 and high Cl concentrations (with HCO_3/Cl ratios mostly <0.05), whereas those at Government Gardens have moderate HCO_3 and Cl concentrations (and HCO_3/Cl ratios of about 1). The bores at Ngapuna and Government Gardens show the same differences as the springs (Figures 4.11-4.13). Government Gardens waters can be produced from Ngapuna-type water by groundwater dilution and rock-water alteration, but cannot be produced from Kuirau-type water, because the former have higher HCO_3 (particularly) and Cl concentrations. Hamiora Baths water is intermediate between Ngapuna and Government Gardens waters, suggesting that it is a mixture of the two. The Cl-B-SO_4 plot (Figure 5.4) also shows a clear distinction between the

Ngapuna and Government Gardens springs, again indicating that the Government Gardens springs have interacted with aquifer rock extensively. The Cl/B ratios are about 140 and 78 respectively for these groups.

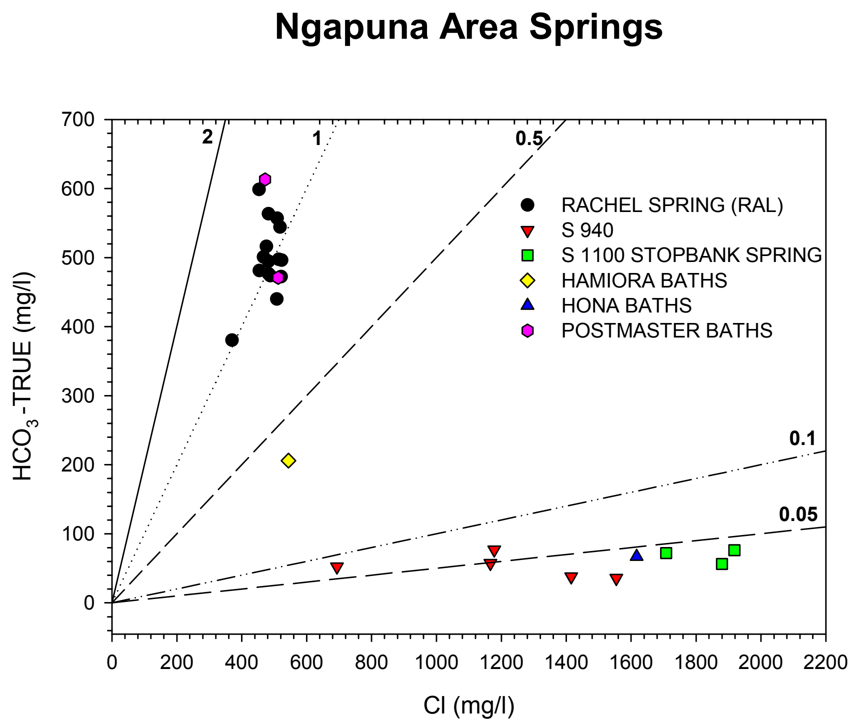


Figure 5.2 HCO_3 (true) vs. Chloride - Ngapuna Springs Area.

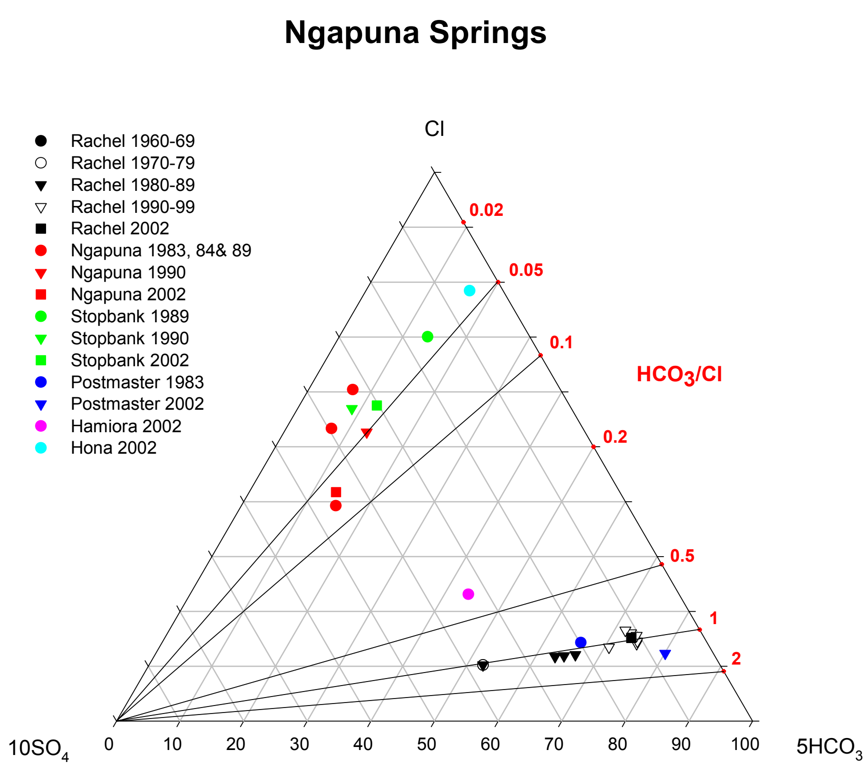


Figure 5.3 HCO3-Cl-SO4 ternary diagram - Ngapuna Springs.

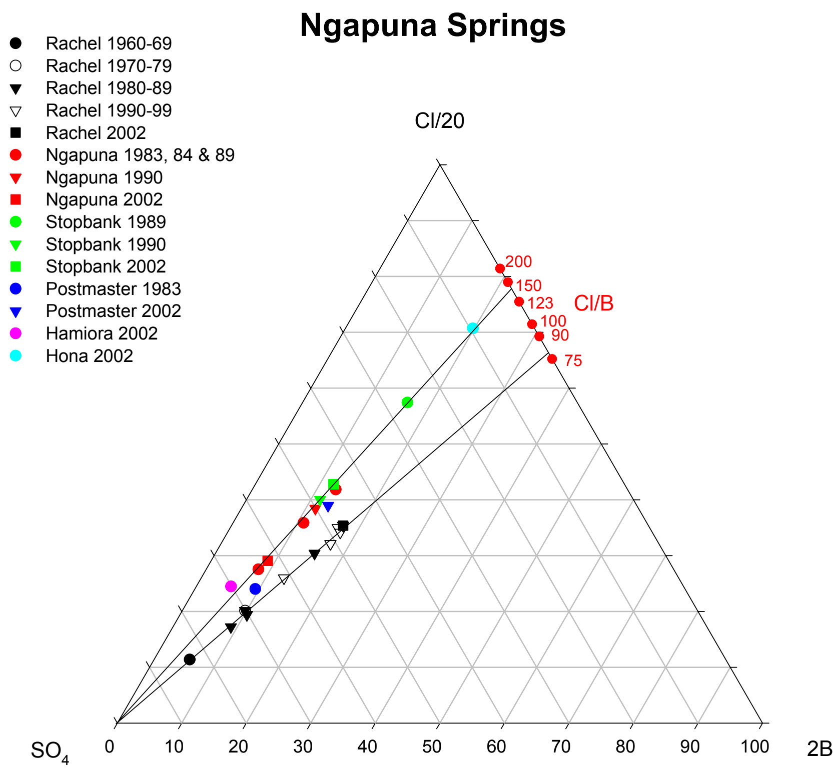


Figure 5.4 B-Cl-SO_4 ternary diagram - Ngapuna Springs.

5.6.2 Whakarewarewa

Whakarewarewa Spring results are plotted as Cl-HCO_3 and Cl-HCO_3-SO_4 ratios as shown in Figures 5.5 and 5.6. The springs have HCO_3/Cl ratios less than 0.5 and form distinct groupings, with some springs on the north end of Whakarewarewa having higher Cl concentrations compared to the majority of the springs at Whakarewarewa. The springs with higher Cl concentrations are found in the Roto-a-Tamaheke area. These springs are S952 (Cl 1000 mg/l, HCO_3 120 mg/l) and Ororea (Cl 800 mg/l, HCO_3 200 mg/l), which appear to be transitional composition between Ngapuna and the main Whakarewarewa springs. The main group of Whakarewarewa springs have almost constant Cl (~560 mg/l) and variable HCO_3 (0-240 mg/l) concentrations, suggesting that the waters are all diluted to the same extent, but have different degrees of rock interaction (neutralisation). The springs with the lowest HCO_3 concentrations tend to be those with the highest sulphate concentrations (see Cl-HCO_3-SO_4 plot Figure 5.6), suggesting that they are affected by near-surface oxidation from the incursion of shallow groundwater.

The main Whakarewarewa springs have lower Cl/B ratios (~ 90) than S952 and Ororea (~123) showing that the former have been more strongly altered by rock-water interaction, as shown in Figures 5.5 and 5.7.

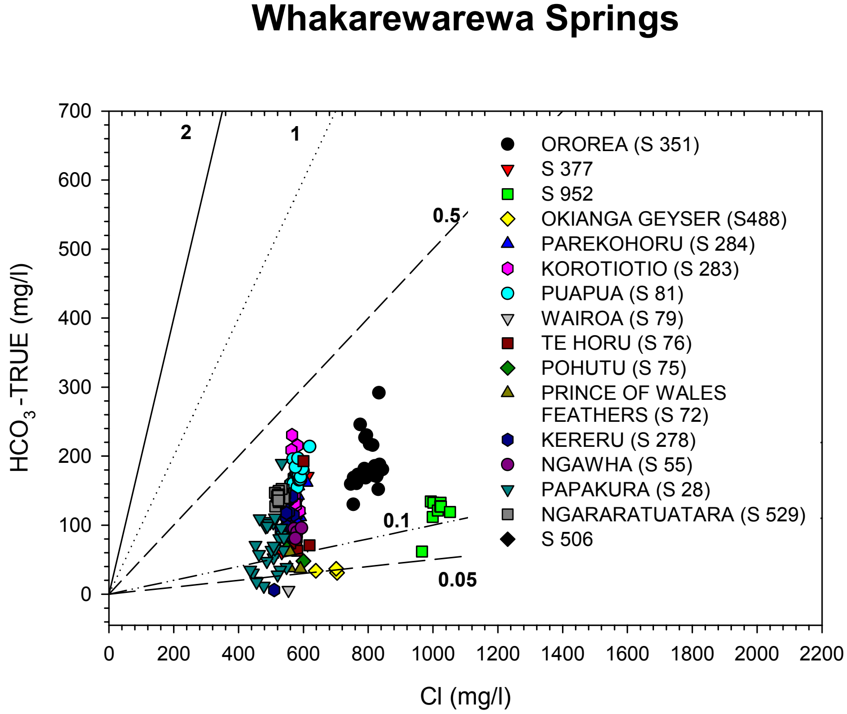


Figure 5.5 HCO3 (true) vs. Chloride - Whakarewarewa Springs.

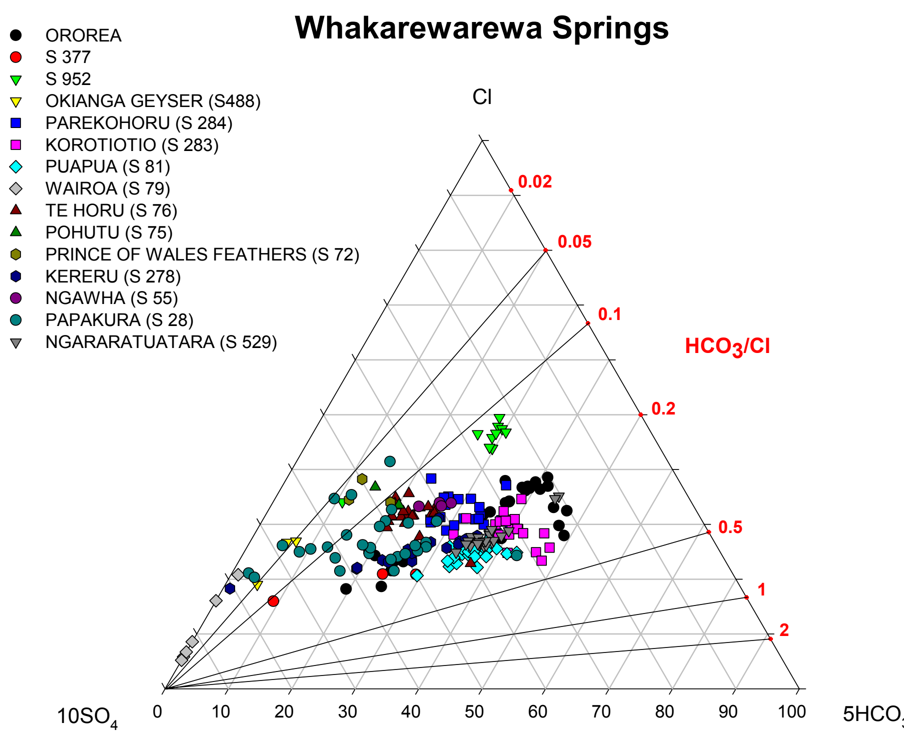


Figure 5.6 HCO3-Cl-SO4 ternary diagram - Whakarewarewa Springs.

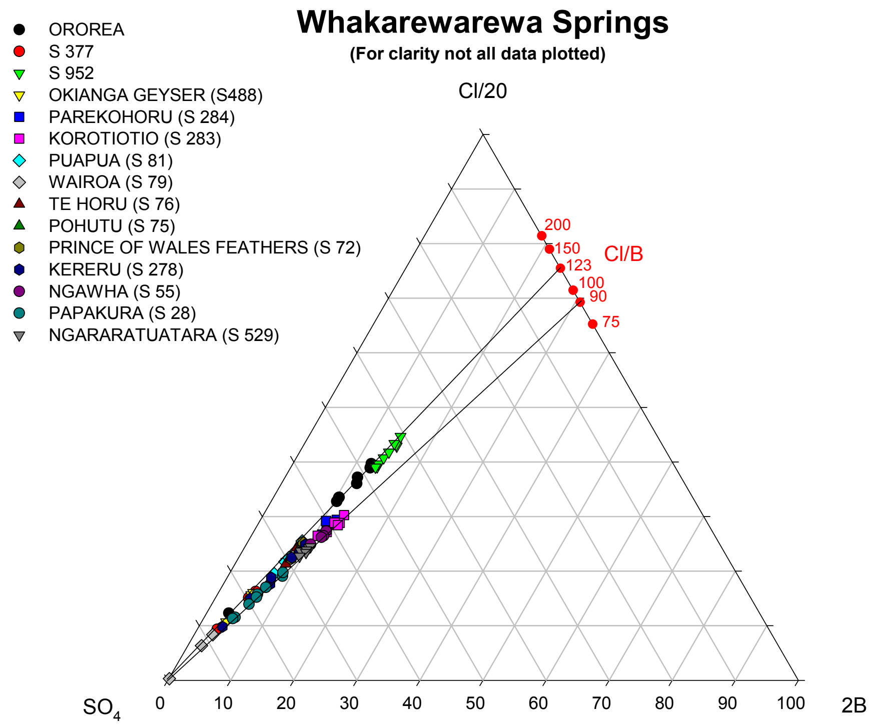


Figure 5.7 B-Cl-SO4 ternary diagram - Whakarewarewa Springs.

Figure 5.7 also highlights the close relationship between S952 and the Ororea springs. These features are also very close (~200m) to each other. However, spring 952 discharges less dilute (higher chloride) fluids. It is likely that it is fed directly from the deeper aquifer as S952 was formed from a nearby bore blow out. Since 1993, S952 fluids have shown a small increase in Na/K geothermometer temperatures (215°C between 1988 and 1993 compared to 222°C in 2002) and likewise a small increase in chloride (1024 to 1052 ppm). In comparison, Ororea spring chloride compositions have decreased since 1993 from 835 ppm to 746 ppm and sulphate has increased from 52 to 256 ppm. This would suggests that the features at Whakarewarewa that are fed from deeper aquifers are now showing recovery but the features that are fed by fluids from shallower depth are taking longer respond to post closure aquifer pressure increases. Gauging of the Puarenga Stream in 2000 suggested a loss of water to groundwater aquifers and perhaps to the deeper geothermal aquifers (Gordon et al., 2001). Nevertheless, the chloride composition and behaviour of S952 and Ororea Springs at Roto-a-Tamaheke as well as other Eastern Whakarewarewa springs suggests that the continued dormancy of few springs and geysers in this area is unlikely to be a result of quenching at depth with cold groundwater.

5.6.3 Kuirau-Ohinemutu

The Kuirau springs have variable HCO_3 (240-360 mg/l), but nearly constant Cl (320 mg/l) fluid concentrations with HCO_3/Cl ratios of about 1 as shown in Figures 5.8 and 4.9. In comparison, Ohinemutu springs have lower HCO_3 (200 mg/l) but similar Cl concentrations and HCO_3/Cl ratios of about 0.6. Samples from bores RR681 and 913 show similar pattern, of Cl and HCO_3concentrations. It is likely that the near constant Cl concentrations either an artefact of limited sampling, or this could indicate an input of two waters with moderate and low HCO_3 respectively, but with similar Cl concentrations. This would result from the same dilution, but different degrees of rock-water interaction. The Cl/B ratios of the Kuirau-Ohinemutu samples are all very similar (about 50) and markedly different from the Ngapuna samples (about 140) as shown by comparing the ternary spring plots in Figures 5.4 and 5.10.

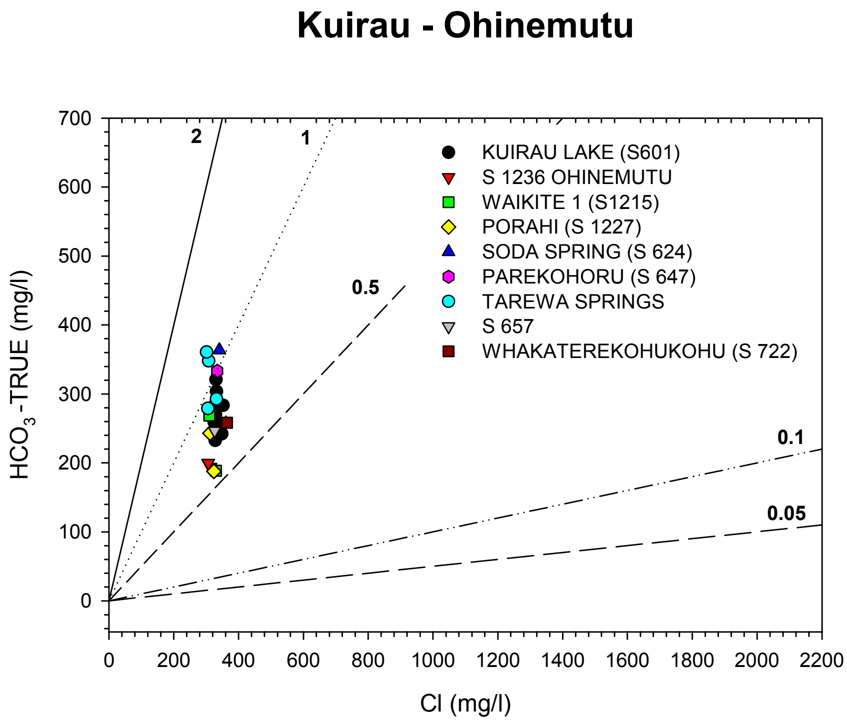


Figure 5.8 HCO_3 (true) vs. Chloride - Kuirau-Ohinemutu Springs.

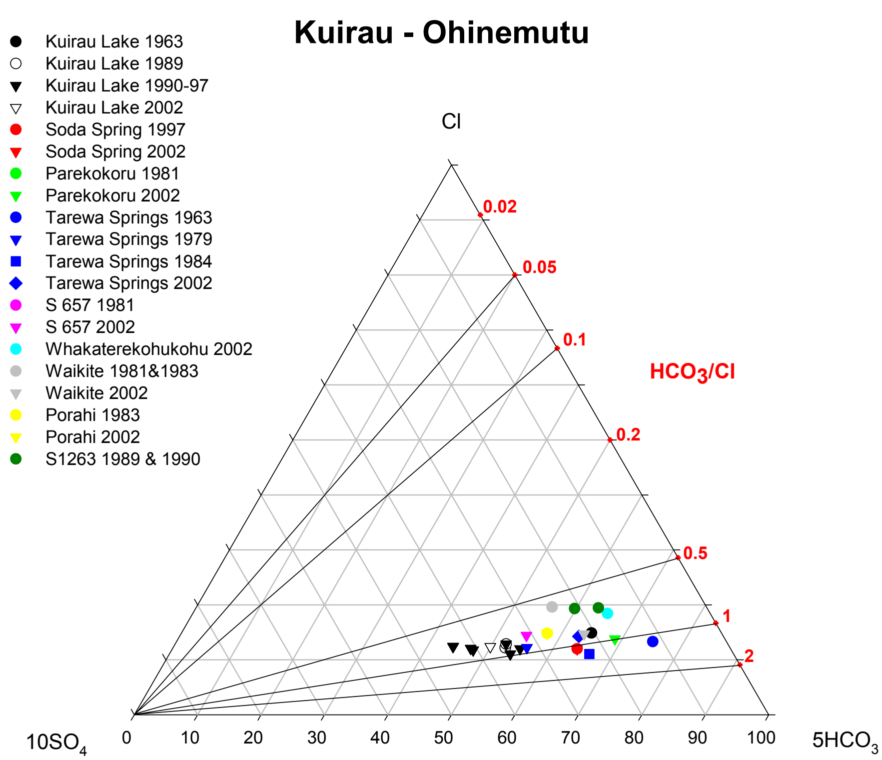


Figure 5.9 HCO_3-Cl-SO_4 ternary diagram - Kuirau-Ohinemutu Springs.

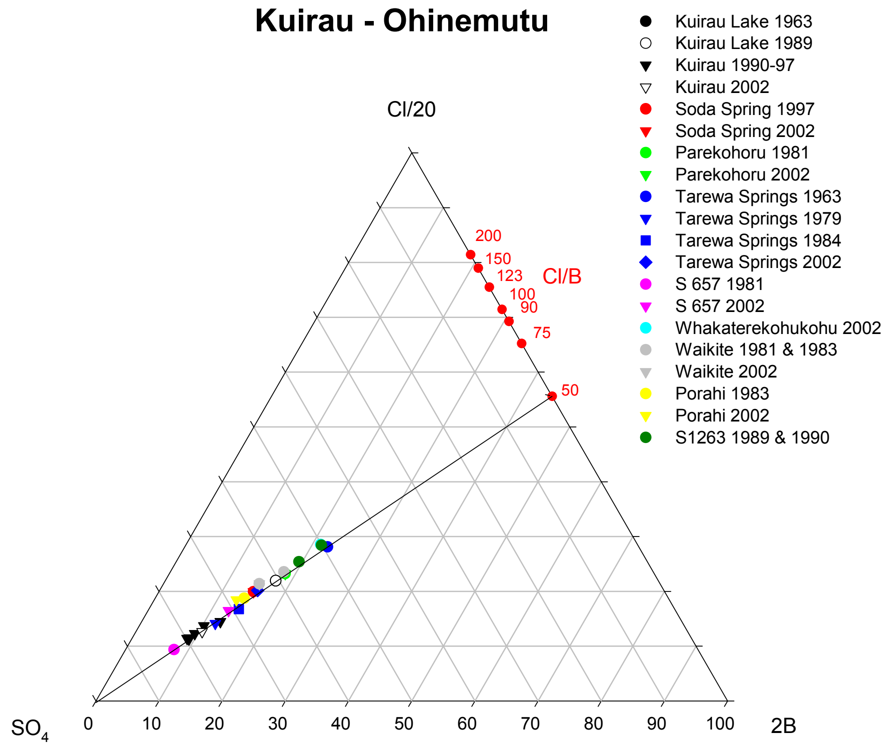


Figure 5.10 B-Cl-SO_4 ternary diagram – Kuirau-Ohinemutu Springs.

5.6.4 Bores

Although the bores cover a wider area than the springs, they were accessible only in areas outside of the Pohutu exclusion zone, so the number of available samples were quite limited. The bore results shown in Figures 5.11 to 5.13 reinforce the spring results from the respective thermal areas. Bores in the Ngapuna-Government Gardens and Kuirau-Ohinemutu areas show the same compositional variations. At Ngapuna, bores RR889 and M25 have similar HCO_3/Cl ratios to Stopbank Spring (S1100), Hona Baths and spring S940, while at Government Gardens, bores RR885 and RR887 follows a similar trend as Rachel Spring and Postmaster Baths (although the springs have higher HCO_3 and Cl concentrations).

At Kuirau area, bore RR681 and RR913 have the same compositions as thermal features; Kuirau Lake (S601), Soda Springs (S624), Parekohoru (S647), Tarewa Springs, S657 and S722. However bores RR741, RR627 and RR865 are located in the mid-region near the saddle between the two buried Rhyolite domes have compositions similar to Kuirau area but contain higher Cl and HCO_3 concentrations. Bores RR653, RR825, RR738, RR816, RR1016 and RR638 are located further south (near the northern edge of the Pohutu exclusion zone) have Cl and HCO_3 concentrations that increase eastwards across the southern Rhyolite dome. However, bore RR638 was previously found to be transitional between the Ngapuna-type and Kuirau-type waters.

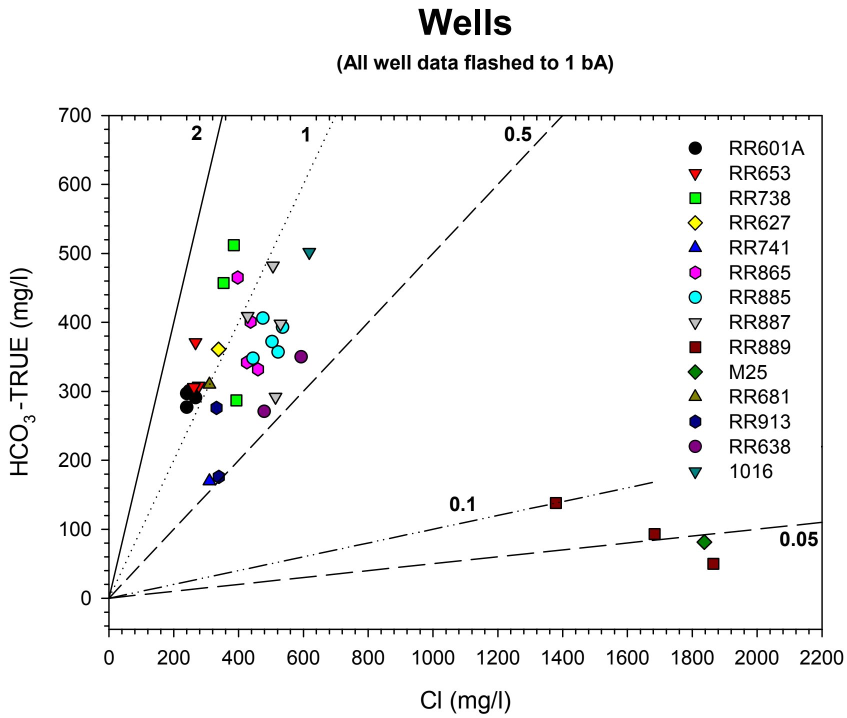


Figure 5.11 HCO_3 (true) vs. Chloride – bores.

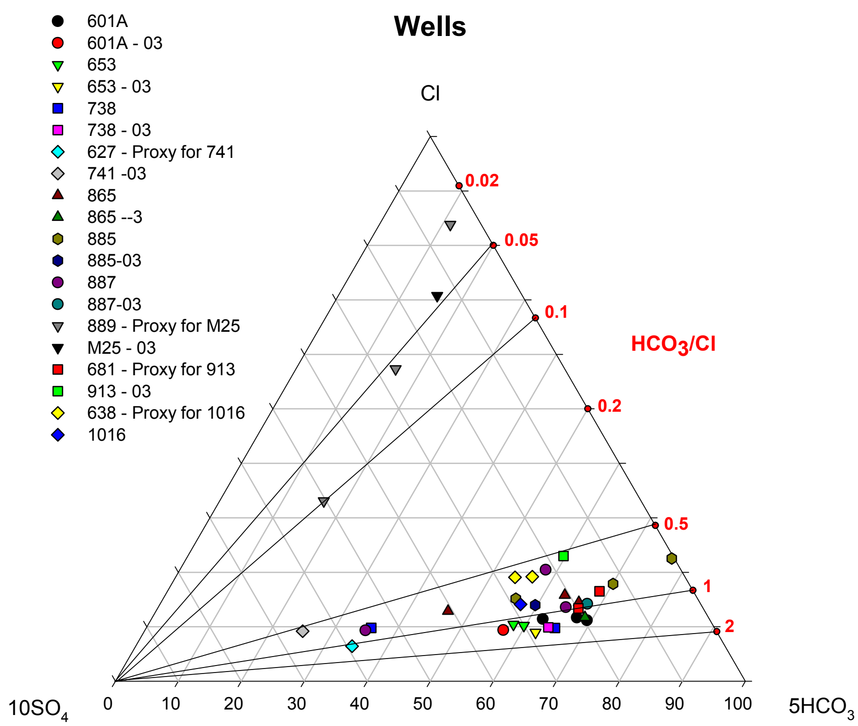


Figure 5.12 HCO_3-Cl-SO_4 ternary diagram – bores.

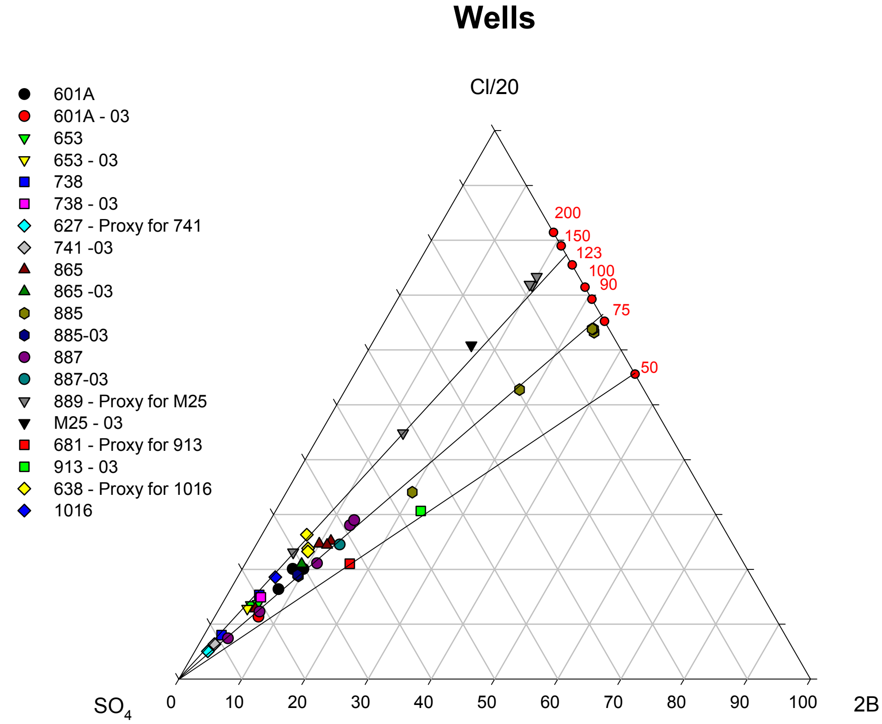


Figure 5.13 B-Cl-SO_4 ternary diagram – bores.

5.6.5 Enthalpy – Chloride Correlations

The aquifer enthalpy (H) is derived from the inferred aquifer temperature, which is calculated using either the quartz or cristobalite silica geothermometer. The measured chloride concentration is reduced to aquifer conditions (Cl (res)) using the aquifer enthalpy assuming there is no excess steam in the reservoir.

A plot of chloride vs. enthalpy for the unboiled fluids discharged by the bores is shown in Figure 5.14. There are two clusters of points, the high chloride – high enthalpy "parent" fluids represented by bores M25 and RR889 and the remaining bore samples representing the cooler fluids which have been diluted from the parent waters. Although there are changes in the reservoir chloride and enthalpy, they are not large and the historical together with the recent data tends to plot in the same portions of the Chloride-Enthalpy diagram. This suggests that there is little change since the bore closure programme and no substantial cooling, reheating or dilution of the aquifers in the feed zones surrounding the bores. Nevertheless there are small decreases in both enthalpy and chloride, mainly in the western Rotorua bores. This may now be the normal pattern with small "natural" fluctuations, but further sampling will determine the trend

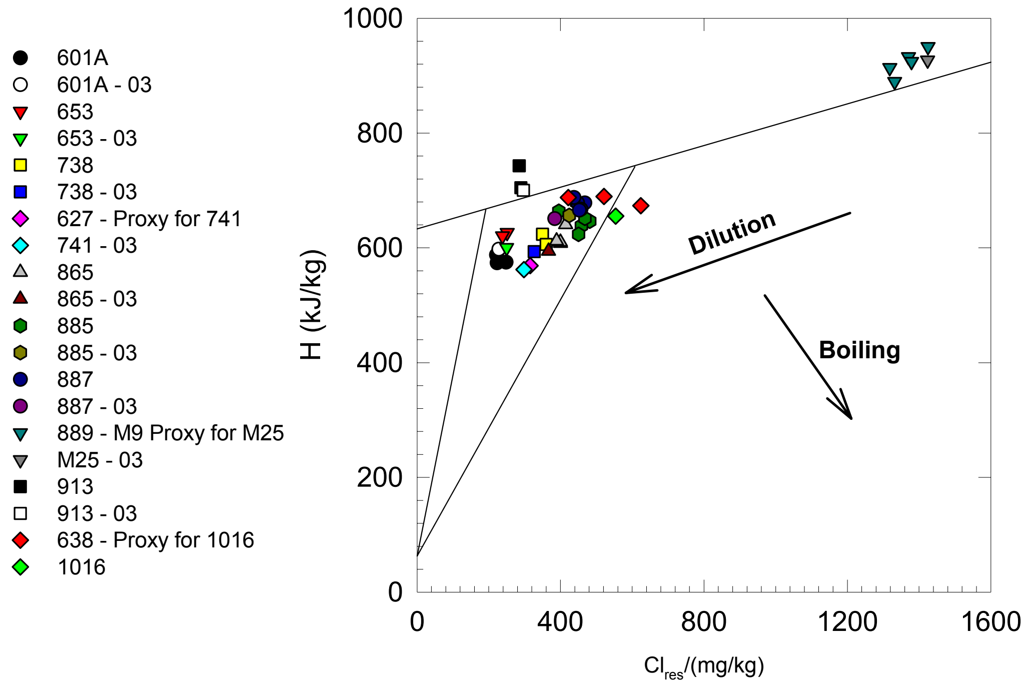


Figure 5.14 Chloride-Enthalpy diagram for the sampled and proxy bores.

5.6.6 Geothermometers

Figure 5.15 is the K-Na-Mg ternary diagram used for evaluating Na-K and K-Mg geothermometer temperatures for bore fluids. This figure clearly shows the high temperature of the M25/RR889 fluids, which lie on the full equilibrium line, separated from the remaining cooler fluids. Bore RR885, in Government Gardens also appears to be fully equilibrated but at lower temperatures. Close agreement can be expected between the fast and slower acting geothermometers if all fluids were at similar temperature for long periods. However there are other effects that could cause an apparent change in geothermometer temperature including removal of Mg in clays and silica during boiling (Giggenbach and Glover, 1992).

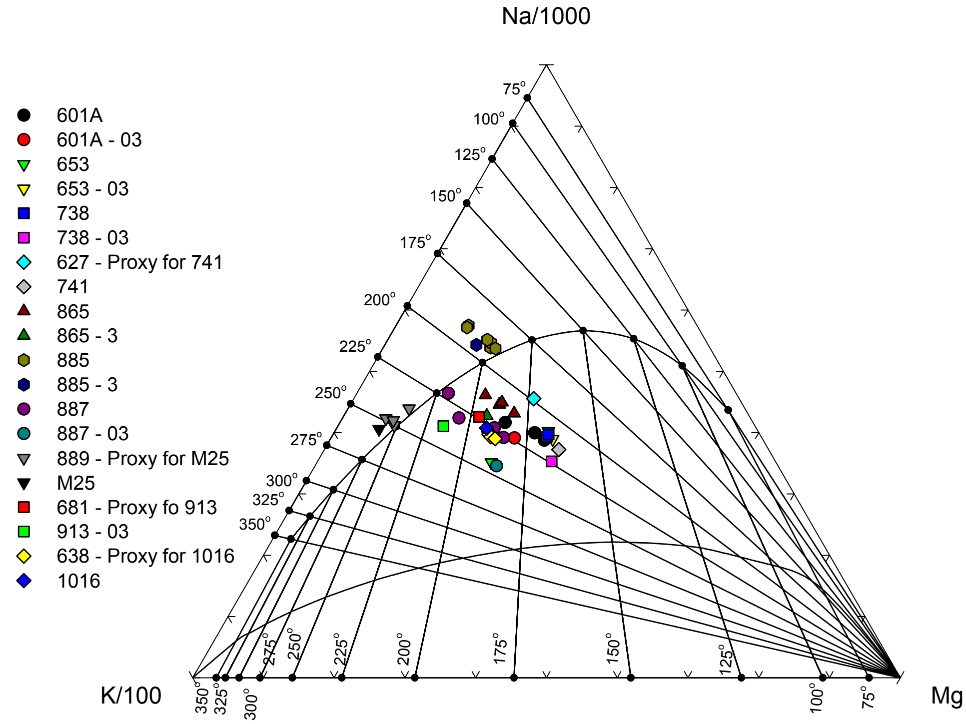


Figure 5.15 K-Na-Mg ternary diagram.

The equations for the cation geothermometers are based on concentration ratios, so that neither boiling nor dilution (with low mineralized fluid) alters the derived temperature, despite affecting the absolute concentrations.

For many of the recently collected samples the derived K-Mg geothermometer temperatures are unchanged since the 1980s while the Na-K temperatures have increased by up to 16^{o}C, which is indicative of an increase in source fluid temperatures in the deep aquifer.

Kuirau bore RR913 has a higher Na/K geothermometer temperature than any of the other western bores and similarly higher silica (cristobalite) geothermometer temperatures (See Figure 5.14). The silica geothermometer reflects fluid aquifer temperatures close to the feed zones of the bore while the Na/K geothermometer reflects the deeper source fluids temperatures. The present downhole temperature of RR913 is unknown.

Using spring compositions for evaluating changes in aquifer temperatures is more problematic than for bores due to possible re-equilibration of the geothermometer to lower temperatures or a switch to a controlling reaction which is different from the one on which the geothermometer is based. Nevertheless the changes observed in the silica as well in Na/K geothermometers correlate well with other changes in compositions, particularly SO_4 and Cl. For example at Pohutu Geyser (S75) the silica geothermometer temperatures have increased since 1984 by 15-20^{o}C to 183^{o}C or 226^{o}C (depending whether cristobalite or quartz is assumed to be the controlling the silica solubility) and an increase of 7^{o}C in the Na/K geothermometer temperature from 246 ^{o}C to 255^{o}C. This has been accompanied by increase in chloride from 549 to 600 ppm with no change in sulphate. These trends signify that a greater proportion of the deeper source fluid is discharging and there is less dilution with shallow low chloride fluids. Other springs showing similar beneficial changes include Parekohoru (S284), Okianga Geyser (S488), Ngararatuatara (S529) and THC Blowout (S952).

5.7 Gas Compositions

In 2003 steam sampling was undertaken so that steam gas compositions could be determined. However the comparison of gas results is restricted due to the paucity of previous data. Giggenbach and Glover (1992) is the only published study to have interpreted the chemistry of the gas discharges and this was based on one limited data set collected in 1989. Based on the relative proportions of argon (Ar), nitrogen (N_2) and helium (He) Giggenbach and Glover (1992) identified three upflow zones; Kuirau Park, Ngapuna and Whakarewarewa. The gases most highly enriched in He were from Ngapuna. However well RR889 (M9) did not fit this pattern and was found to be in the group most depleted in He and contained a high proportion of atmospheric gases (see Figure 7 in Giggenbach and Glover; 1992). Figure 5.16 shows that the present M25 (replacement well for M9) value now plots well into the He enriched field, suggesting that the previous RR889 results were either incorrect or subject to exploitation induced processes (e.g. production of previously boiled fluids) as suggested by Giggenbach and Glover (1992).

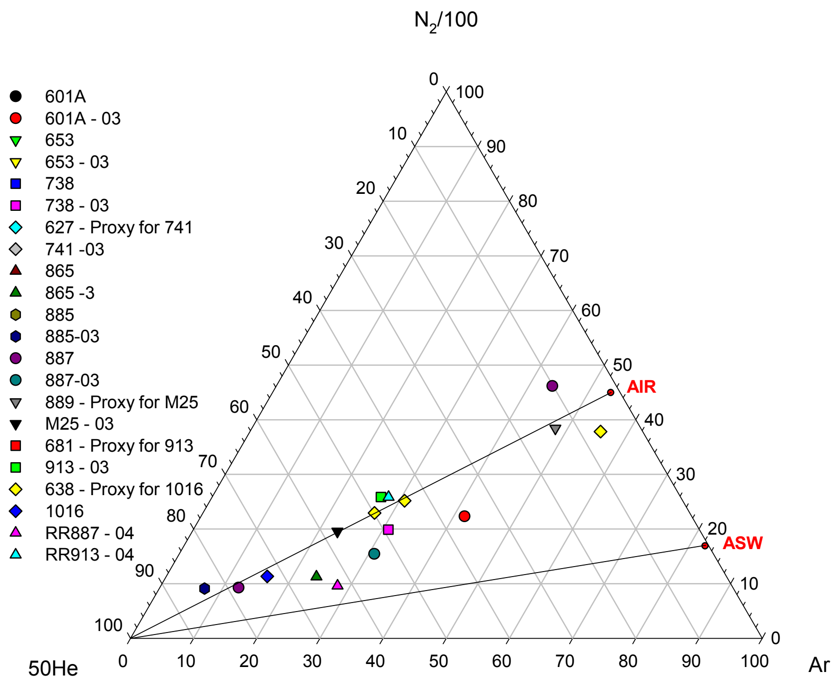


Figure 5.16 Ar-N_2-He ternary diagram.

To the northeast at Ngapuna very high He enrichment was found in bores RR1016, RR887 and RR885 with particularly high enrichment in bore RR885. He enrichment was also reported by Giggenbach and Glover (1992) in surface features in the Ngapuna area. Two previous samples exist for RR887, one very enriched in He and the other contaminated with air so perhaps this area was always enriched with He. Giggenbach and Glover (1992) sampled bore RR877 ("Polynesian Pool"), but this sample is highly depleted in helium and plots near the relative proportions of air, unlike the 2003 sample from RR887 which lies 114 metres to the east of RR877. In November 2004 further steam samples were collected from bores RR887 and RR913 and both show similar results to those observed in 2003. There was also relatively high enrichment of He for the western bores that could be sampled. In particular, bores RR1016 and RR865 are enriched in He compared to Kuirau or Whakarewarewa features but are similar to Ngapuna, as reported by Giggenbach and Glover (1992). RR638, the nearby comparison well for 1016, is less enriched but still lies in the same "Kuirau" region of the diagram, as does RR738.

This data suggests that the "upflow" zones identified through enrichment of He relative to Ar and N_2 may cover a wider and more diffuse geographic area than previously identified. The mobility of steam means that gases respond much more quickly than fluids to field wide perturbations. However the small number of bores available for sampling and a paucity of temporal data means that this conclusion is not certain.

Relative H_2S-CH_4-CO_2 compositions were used by Giggenbach and Glover (1992) to show that fluids over the eastern part of the field are degassed with respect to methane (CH_4), which they inferred was due to boiling in the upflow zone. The equilibration of the gases at high temperatures to explain the relative loss of sparingly soluble CH_4 was discounted because there was no shift observed towards the CO_2 apex of the diagram. H_2S is considerably more soluble than CO_2 so that boiling results in a relative decrease in CH_4 and an increase in H_2S. In contrast, at Kuirau the high relative enrichment in CH_4 was interpreted to have been due to fluids ascending without boiling. As shown in Figure 5.17, the present data fits in with the trends identified by Giggenbach and Glover (1992). The Kuirau samples from bores RR913 and RR601A are relatively enriched in CH_4 ($CO_2/CH_4 \approx 50$-100), while Ngapuna well M25 is depleted in CH_4 ($CO_2/CH_4 \approx 1000$). Bores with intermediate ratio ($CO_2/CH_4 \approx 500$), include the western bores, RR885, RR738 and 1016 (and proxy 638) but all are enriched in H_2S, and bore RR738 with the highest enrichment. Samples for RR887 are the mostly depleted in CH_4 ($CO_2/CH_4 \approx 2500$).

The relative enrichment of methane in the steam phase provides strong evidence for a deep upflow zone in the west, at Kuirau, separate from that at Whakarewarewa and Ngapuna. The suppression of boiling at depth allows the dissolved CO_2 to react with rocks to form the high bicarbonate concentration found in the Kuirau fluids as discussed elsewhere in this chapter.

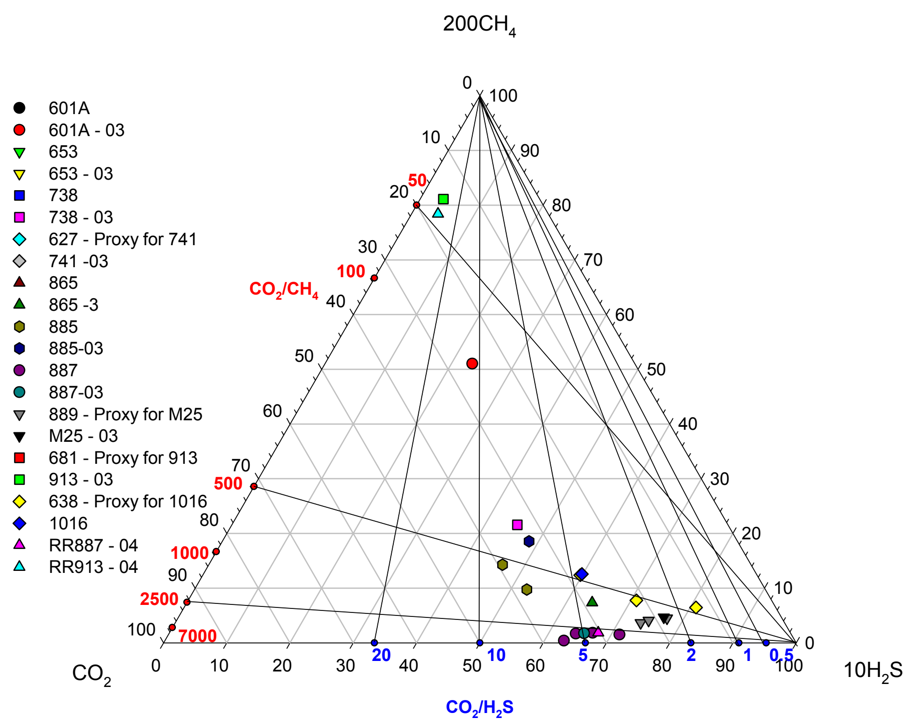


Figure 5.17 H_2S-CH_4-CO_2 ternary diagram.

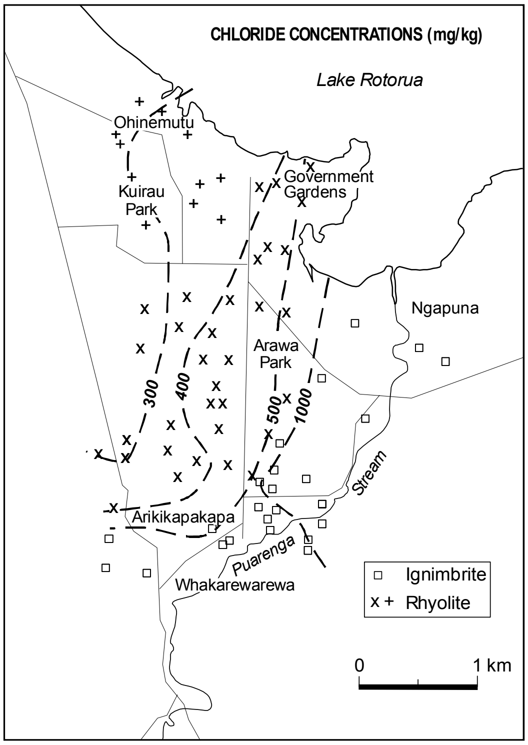
5.8 Discussion

Giggenbach and Glover (1992) have established that there are two fundamental water types of water in the RGF; an alkali-chloride water as seen in many of the "rift" type geothermal fields on the west side of the Taupo Volcanic Zone (Wairakei, Mokai, etc.), and a more altered bicarbonate-chloride, water previously seen in bicarbonate-rich springs (Waikite). Giggenbach and Glover (1992) also consider that both these water types are derived from the same source at depth. The nature of these waters as they approach the surface is controlled by the geological structure, rocks properties and field hydrology (Wood 1992, Stewart *et al*. 1992). Understanding the hydrology of the deeper aquifer is problematic because the geological structure and rock properties are unknown below 300 m.

However, the shallow geological structure has been described by Wood (1992) as Mamaku Ignimbrite to the east stepping down beneath the Rotorua Rhyolite domes beneath Rotorua City, which are both covered by Rotorua Basin Sediments. The ignimbrite has high permeability and porosity due to fracturing and partial welding following its emplacement. This fracturing is also likely to provide permeability at deeper levels. The rhyolite domes are brecciated and highly fractured in their upper 40 m, while massive and weakly fractured below. Therefore the permeability is better in the upper 40 m.

The Kuirau Fault on the west side of the Pukeroa north rhyolite dome channels hot fluids upwards to the Kuirau and Ohinemutu areas. There may also be permeability on the east side of the domes allowing passage of hot fluids. The Rotorua Basin Sediments are a layered sequence of mixed primary and redeposited tephra, alluvium and lake sediments. The range of sediment types is wide, and permeability and porosity are dependent on the proportions of fine and coarse sediments. Sediments on the west side of the south rhyolite dome are comprised of predominantly coarse sands with relatively high permeability and porosity; those on the east side of the domes and overlying the north dome are mainly fine muddy sediments with poor permeability and porosity. Wood (1992) reports a temperature anomaly in the Kuirau area again supporting an upflow in this area.

The most striking comparison is between the Ngapuna and Government Gardens areas where the two types of water are seen in their most extreme forms within a short distance of each other. The highest chloride concentrations in alkali-chloride waters are resident in the ignimbrite below Ngapuna, and the most concentrated altered bicarbonate-chloride waters are within the east side of the north rhyolite dome beneath the Government Gardens area. Wood (1992) has shown that the water temperatures are high on the east and west sides of the north rhyolite dome and lower in the middle (by 50-60^{o}C), clearly showing that the (altered bicarbonate-chloride) water is sourced independently on each side of the dome. In contrast in the south dome, higher temperatures occur on the eastern side, which decrease evenly across the dome. This clearly indicates that the water is sourced on the east side. Colder water which is sourced from the coarse sediments on the west side of the domes and possibly from deeper sources, flows into the domes from the west side, particularly in the saddle area between the domes. The change in chloride and bicarbonate across the field is illustrated in Figure 5.18.



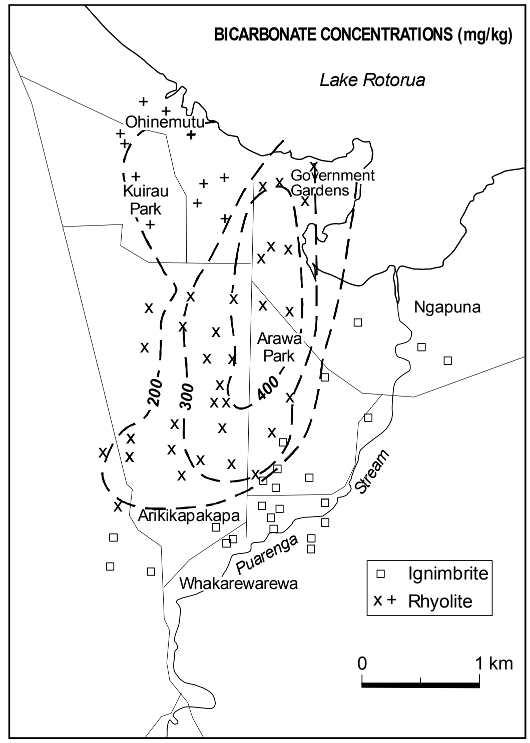


Figure 5.18 Contours of constant chloride and bicarbonate.

This analysis shows clearly that there are deep sources feeding altered bicarbonate-chloride water to both sides of the northern rhyolite dome and to the east side of the southern rhyolite dome. These waters are generated by dilution and cooling of the alkali-chloride water followed by prolonged interaction with rock at lower temperature. The waters are highly reactive because of their high dissolved CO_2 contents and the lower temperature. The question of how deep this occurs is difficult to answer without more information on the conditions at depth, but possibly 1-2 km depth is a reasonable estimate. The alkali chloride water at Ngapuna on the other hand is water that has had little or no dilution with groundwater and the waters are less reactive because of their lower dissolved CO_2 contents because of boiling as it rises.

5.9 Summary Conclusions

(a) The chemical and isotopic data incorporating the historical and recent bore and spring results supports previous work that indicates that at least two separate plumes make up the overall Rotorua system (Wood, 1992 and Giggenbach and Glover, 1992). The primary upflow is to the east of the Rhyolite Domes, and then subsequently flows southeast to Whakarewarewa. The smaller separate upflow to the Kuirau area is chemically distinct, although the geological evidence (Wood, 1992) suggests that they are hydrologically connected. Excessive exploitation of one is likely to cause significant changes in the primary upflow that supplies Whakarewarewa (Giggenbach and Glover, 1992).

(b) The chemical evidence shows that the fluids discharged in the northern area of the field at Kuirau Park now match those discharging in the early 1960s and it is likely that this part of the field is near full recovery.

(c) The Whakarewarewa springs do not appear to be fed directly by a primary upflow and consequently the recovery has been mixed as the hydrology between the upflow and the surface outlets are influencing conditions. However recovery has been particularly notable at Parekohoru and Pohutu, but also evident for Okianga Geyser, Ngararatuatara and THC Blowout, with increases in aquifer (geothermometer) temperatures and a greater proportion of deep geothermal fluid being discharged.

(d) The shallow aquifer feeding the bores over the last decade shows relatively minor changes in reservoir chloride and small increases in heat (~16^{o}C). This indicates stability and no deleterious processes are affecting the RGF.

(e) The withdrawal of fluid from the shallow aquifers during the exploitation phase did not change significantly the composition or chemistry of the deep aquifer fluid.

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Chapter 6: Soil Gas from the Rotorua Geothermal Field

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6.1 Introduction

Resistivity data shows that the RGF (~28 km^2) underlies the entire area of the city and extends at least 2 km northward under Lake Rotorua (Bibby et. al., 1992). The geothermal manifestations of this deep plume at the surface are isolated to three main areas shown in Figure 5.1. Within these areas the temperature at 1-m depth was at least five degrees C over ambient temperatures during a survey in 1971 (Thompson, 1971). Soil gas concentrations of CO_2 and H_2S were found to be elevated locally at sites within these geothermal areas (Finlayson, 1992), and is the result of separation of the gas phase as the fluid rises to the surface in upwelling zones. Geothermal fluid is primarily hosted in the Mamaku Ignimbrite and the post-caldera rhyolite domes. The upflow of hot water and gases from deeper in the field is thought to be partially controlled by the location of the post-caldera rhyolite domes.

Current models of the field suggest that fluids rise east of the city from fractures and fault structures in the Mamaku ignimbrite. The fluid then flows westward in the ignimbrite until reaching the location of the buried rhyolite domes to the west (Wood, 1992). Fluid then rises along the eastern side of the domes, surfacing near the Government Gardens/Ngapuna and similar flows occur towards the Whakarewarewa and Arikikapakapa areas. The rhyolitic domes are fractured which provides preferential pathways for the release of deeply derived fluids and gas. An additional upflow is located in the Kuirau Park region along the western edge of the northern rhyolite dome where a fault is inferred (Wood, 1992). However, geochemical analyses of fluids support chemically discrete upflows in these three thermal areas with the main parent upflow to the east (Giggenbach et. al., 1992, Mroczek et al chapter 5). Degassed geothermal waters exist at relatively cooler temperatures within the northern and southern rhyolite domes aquifers beneath the greater Rotorua City. These aquifers are used for domestic and commercial uses (Gordon et al 2001).

The aim of this study was to better define the overall levels of gas emissions in the Rotorua area. Gas emission studies are important for defining baseline activity for the volcanic system as well as defining health risks associated with living in active geothermal areas. Therefore, this study focused on assessing CO2 flux levels that occur across the RGF. The intense development of the City has modified the natural gas emission pathways. The present study can be used to indicate spatial extent, and magnitude of gas fluxes that occur across the city of Rotorua. Carbon dioxide fluxes were measured at 952 locations across the greater RGF during 2003. Measurements using 20-50 m spacing were concentrated in regions that previously exhibited elevated levels of carbon dioxide in soil gas. Measurements were also collected across the greater Rotorua city area using a100-200 m spacing.

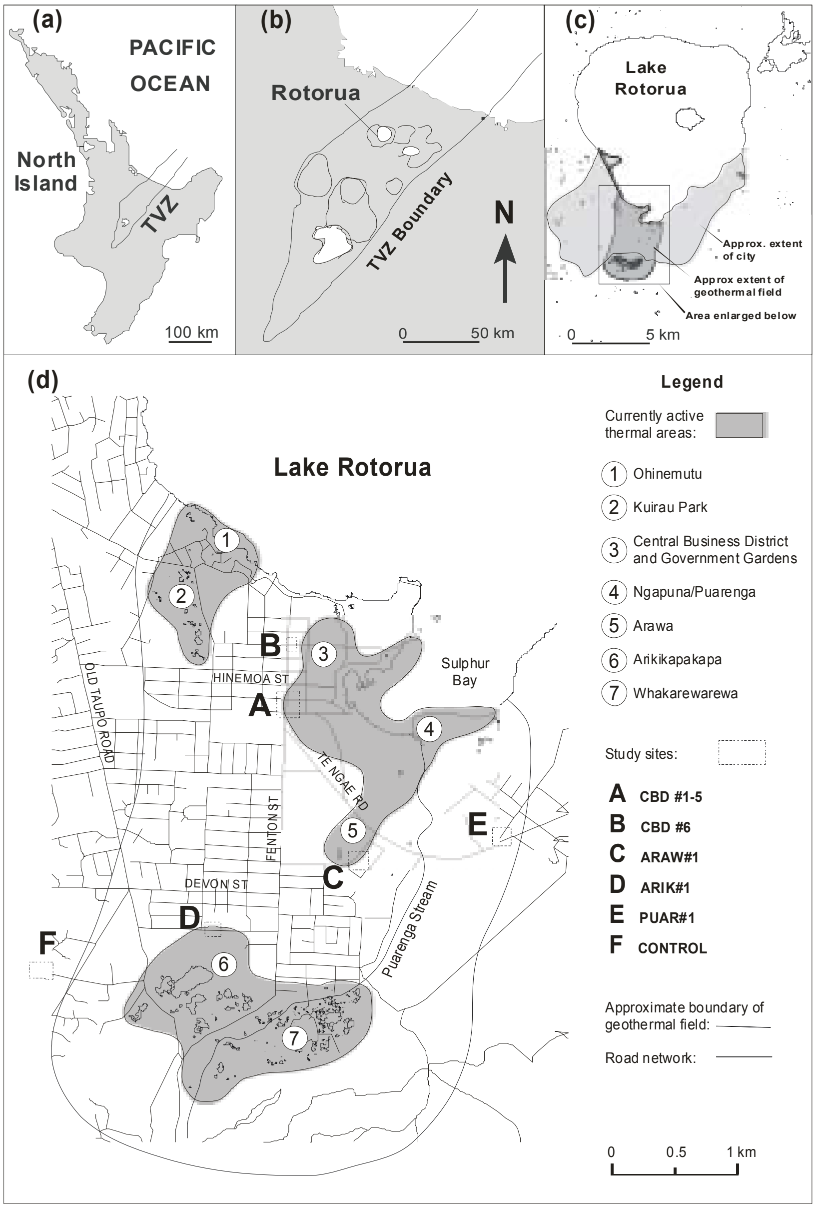
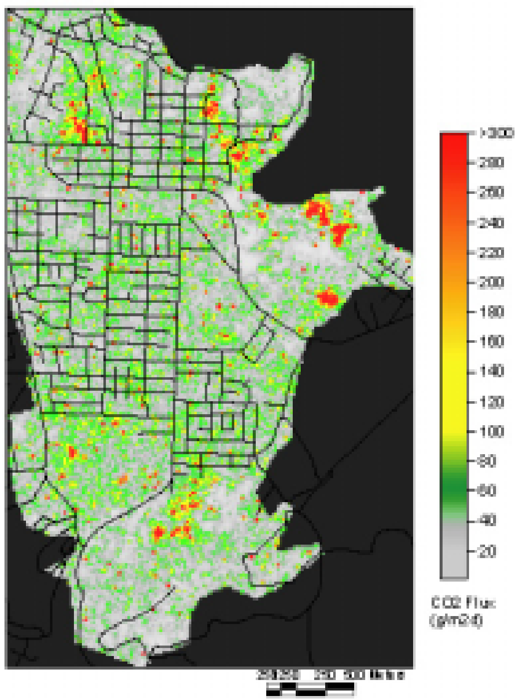


Figure 6.1 *Location of the RGF. (a) shows the position of the Taupo Volcanic Zone (TVZ) within the North Island of New Zealand, (b) shows the Rotorua caldera boundary in context of other volcanic calderas in New Zealand, (c) light grey is the extent of the city and the dark grey is the extent of the subaerial portion of the geothermal system, and (d) shows the street map of Rotorua City and the major regions of thermal manifestations with in the central Rotorua city limits (modified from Durrand and Scott, 2003, capital letters were their sample sites).*

6.2 Results

CO_2 fluxes and soil temperatures ranged from not detectable to 11535 $gm^{-2}d^{-1}$ and 5 to 100°C, respectively. The distribution of fluxes was positively skewed, meaning that there are relatively few high measurements compared to the majority. CO_2 fluxes were spatially variable across the study area, but generally highest in previously defined thermal areas (Figure 6.2). Fluxes measured in the Ngapuna area were higher than in other thermal areas of the field. For example, 12 measurements exceeded 1000 $gm^{-2}d^{-1}$ at Ngapuna, compared to the other thermal area, which had less than 2 measurements over this value. Areas of high flux extended over hundreds of meters in previously defined areas of gas emission (e.g., Ngapuna, Whakarewarewa as shown Figure 6.2), and were typically consistent with known thermal areas containing surface activity. Isolated elevated CO_2 gas fluxes were also measured across the remainder of the RGF but were typically found not to extend more than 25-50 meters.



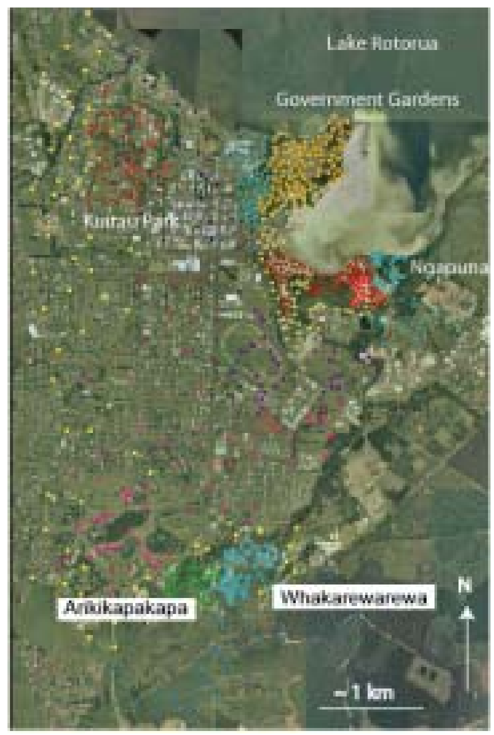


Figure 6.2 Air photo of the Rotorua City. Each flux measurement location is shown with a dot. Map of CO_2 fluxes modelled for the Rotorua region (left). Each colour represents one day of sampling (right).

A weak correlation existed between the log of CO_2 fluxes and the log of soil temperatures as shown in Figure 6.3. Generally fluxes greater than100 $gm^{-2}d^{-1}$ had soil temperatures that exceeded 20°C at 10 cm depth. Interestingly, the two highest fluxes were measured in an area with relatively cool soil temperatures.

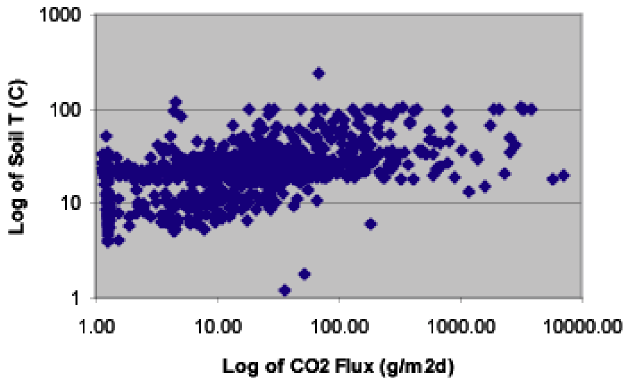


Figure 6.3 Log of soil temperatures plotted against log of CO_2 fluxes.

6.3 Discussion

The levels of CO_2 flux measured in the RGF are as high as those measured on active volcanoes (e.g., maximum measured fluxes at White Island were ~ 8000 $gm^{-2}d^{-1}$, (Werner et.al. 2004)) and are up to 3 orders of magnitude higher than typical biogenic fluxes (e.g., Raich and Schlesinger, 1992). The measurements of CO_2 flux across the RGF are consistent with previous models of upflow of geothermal fluids in mapped geothermal areas. The Ngapuna area displayed the highest fluxes, and the greatest number of high fluxes of any area in the study, suggesting that the Ngapuna area is likely to be the main upflow for the Rotorua geothermal field, releasing the greatest proportion of CO_2 from the geothermal fluids with depressurization and boiling (e.g. Finlayson, 1992). This finding is also consistent with the high Cl being observed in the springs in the Ngapuna region (Mroczek et al this volume).

High fluxes were also observed at Whakarewarewa, Arikikapakapa Golf course, and Kuirau Park. All these area had CO_2 flux less than 3000 $gm^{-2}d^{-1}$ which suggests that fluid supply to these areas are likely to be partially degassed compared to Ngapuna. A concentrated zone of moderately high (max = 350 $gm^{-2}d^{-1}$), yet spatially extensive, flux was also observed in the Government Gardens area, which coincides with the edge of the northern rhyolite dome. Our data supports the existence of a secondary upflow at this boundary, and that these fluids are likely to be somewhat degassed compared to those supplying the Ngapuna region.

The high soil gas fluxes observed in the northern portion of the Arikikapakapa are considered to result from upflow along the boundary of the southern dome (Finlayson, 1992), but there is no evidence that these fluids are any more degassed than those supplying Whakarewarewa. High CO_2 fluxes observed in Kuirau Park and are consistent with models of upflow along the Kuirau fault as mapped by Wood (1992).

Isolated patches of high CO_2 flux occur across the greater field. These isolated patches mapped here do not seem to have any particular spatial arrangement, but are consistent with the existence of high gas concentrations in bores in the central city (Glover and Heinz, 1985). These localised patches of high flux are small in spatial extent (typically < 50 m) and may pose a risk if gas is allowed to build up in enclosed spaces. This identified risk is consistent with the recent preliminary building gas investigation, where elevated levels of CO_2 and H_2S were found in enclosed spaces (Durand and Scott, 2003).

6.4 Conclusions

(a) The levels of CO_2 flux measured in the RGF are as high as those measured on active volcanoes and are up to 3 orders of magnitude higher than typical biogenic fluxes.

(b) Flux measurements and modelling results in this study concur with previous soil CO_2 flux measurements for the field with the highest CO_2 emissions associated with known areas of surface geothermal activity.

(c) The highest fluxes were measured in the Ngapuna area suggesting that upflow into this area is the primary upflow, being the least degassed. This conclusion is consistent with the fluid chemistry as reported in chapter 5 of this report.

(d) High fluxes were measured in the Whakarewarewa, Arikikapakapa, and Kuirau Park areas suggesting partially degassed fluids supplying these regions.

(e) The greatest extents of degassing areas were observed in known geothermal areas but elevated levels of soil CO_2 flux were also observed in isolated patches throughout the field These isolated patches do not seem to have any particular spatial arrangement, but are consistent with the existence of high gas concentrations associated with bores.

6.5 Acknowledgements

Data collection was organized and completed through the dedicated efforts of Karen Britten, Dan Britten, and Geoff Kilgour. Brad Scott, for suggesting this project and providing logistical support and background information. Data were acquired for this study through the GeoNet Project to facilitate research into geological hazards and risk. GeoNet is sponsored by the New Zealand Government through its agencies: Earthquake Commission (EQC), Geological & Nuclear Sciences Ltd (GNS), and Foundation for Research, Science & Technology (FRST).

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Chapter 7: Bore Usage Changes

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7.1 Introduction

This chapter discusses current geothermal usage patterns in Rotorua and compares them to information recorded for the 20 year period 1985 to 2005, where appropriate. Comment is also made on projected future changes in usage of the Rotorua Geothermal Field. Almost all of the usage is from bores drilled into the field with a small number of permits issued from springs and other surface features.

Comparison between usage figures for 2001 and 2005 and those recorded for previous periods are problematical as different field management regimes and legislative structures have been in place over the twenty year period as discussed in chapter 1. The Rotorua Geothermal Regional Plan becoming operative on 1 July 1999 was 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.

7.2 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.

7.3 Bore Location

Figures 7.1, 7.2 and 7.3 show the distribution and density of geothermal bores in 1987, 2001 and 2005 respectively.

Changes between 1985 and 2001 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 2001 and 2005 are less dramatic. Where changes are evident is a small increase in the number of sites within the 1.5 kilometre zone. These are not new wells but are related to identification of previously unknown sites, which have been in operation since before 1992. A number of these sites have been identified during Environment Bay of Plenty compliance monitoring surveys and when properties change ownership.

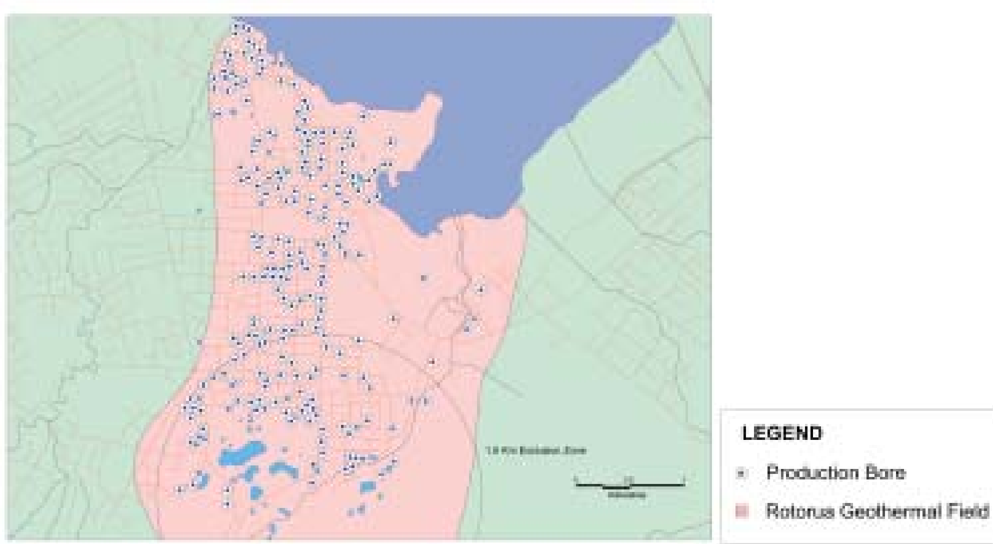

Figure 7.1 Distribution and density of geothermal bores across the Rotorua geothermal field in 1987.

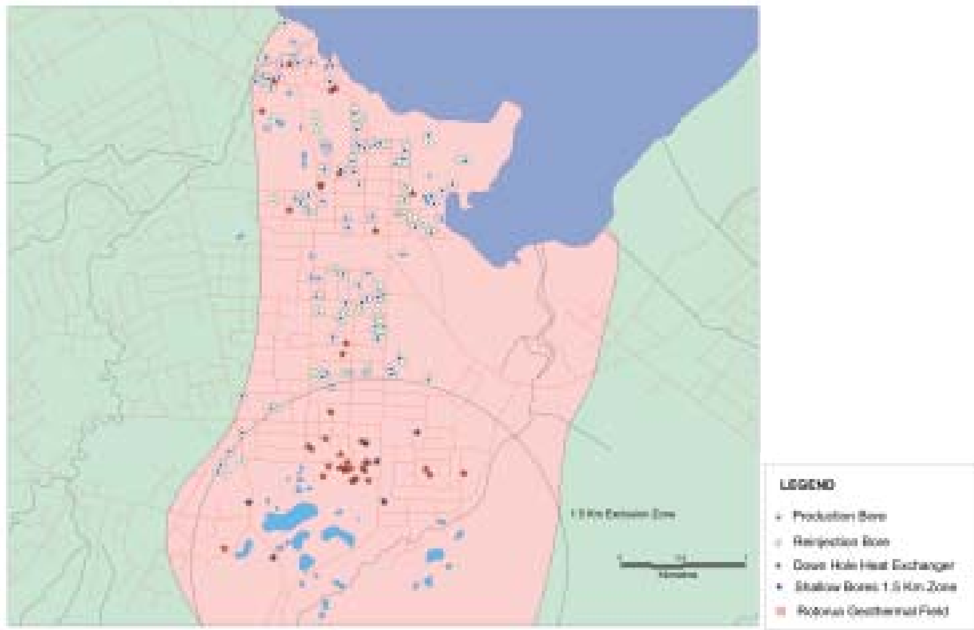

Figure 7.2 Distribution and density of Geothermal bores across the Rotorua geothermal field in 2001. Note the increased use of reinjection bores and bores with downhole heat exchangers and the absence of production bores within the 1.5 km exclusion zone.

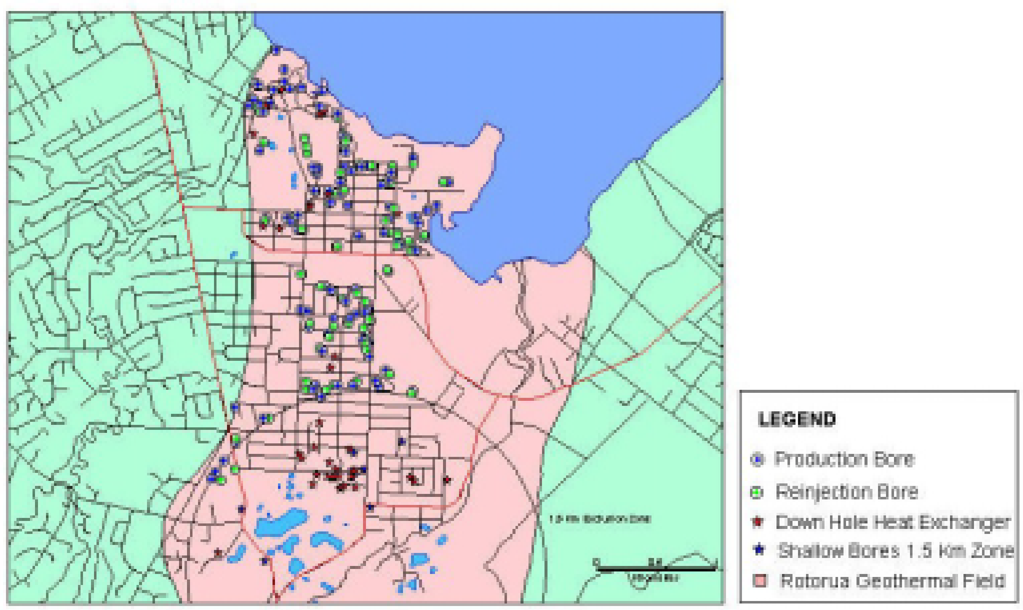

Figure 7.3 Distribution and density of geothermal bores across the Rotorua geothermal field in 2005. Note the increase in the number of reinjection bores compared to the distribution in 2001.

7.4 Number of Production Sites

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, the use of actual bore number is not useful. 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 7.1).

Table 7.1 Production sites in the Rotorua Geothermal Field – 2001/2005.

	Number of Sites – 2001	**Number of Sites - 2005**
Number of production bore sites	144	**140**
Number of reinjection bore sites	68	**86**
Number of down hole heat exchangers	41	**42**

The number of bore sites has remained relatively static since 2001. New sites have been developed and a number of sites have been closed down and bores grouted out. The biggest single change between 2001 and 2005 is the significant increase in Reinjection sites (Figures 7.2 and 7.3).

7.5 Bore Ownership

Table 7.2 Percentage of well ownership in the Rotorua Geothermal Field.

	Years			
	1985	**1992**	**2001**	**2005**
Domestic Bores%	50	54	54	51
Commercial Bores %	50	46	46	49

Table 7.2 compares the percentage of geothermal bores by ownership in 1985, 1992, 2001 and 2005. If a bore has any commercial user drawing from it, then it is classified as commercial. The table indicates there has been a slight decrease in the proportion of domestically owned bores between 2001 and 2005. If the down hole heat exchangers are taken out of the tally, then of the sites extracting fluid, 70 percent are operated by commercial users.

7.6 Total Withdrawal

Table 7.3 Geothermal withdrawal in Rotorua between 1985 and 2005.

	Years			
	1985	**1992**	**2001**	**2005**
Total Withdrawal (tonnes per day)	29,000	9,100	9,800	9,700
Net Withdrawal (tonnes per day)	27,500	3,800	1,900	970

Table 7.3 and Figure 7.4 compares the total volume of geothermal fluid withdrawn from the field in 1985, 1992, 2001 and 2005. 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 2005 estimates are 9,700 tonnes per day and this includes 450 tonnes allocated to Polynesian Spa Limited for abstraction from the Whangapipiro (Rachel) Spring.

7.7 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 7.4. The current net mass withdrawal is now only 3.5 percent of the 1985 total.

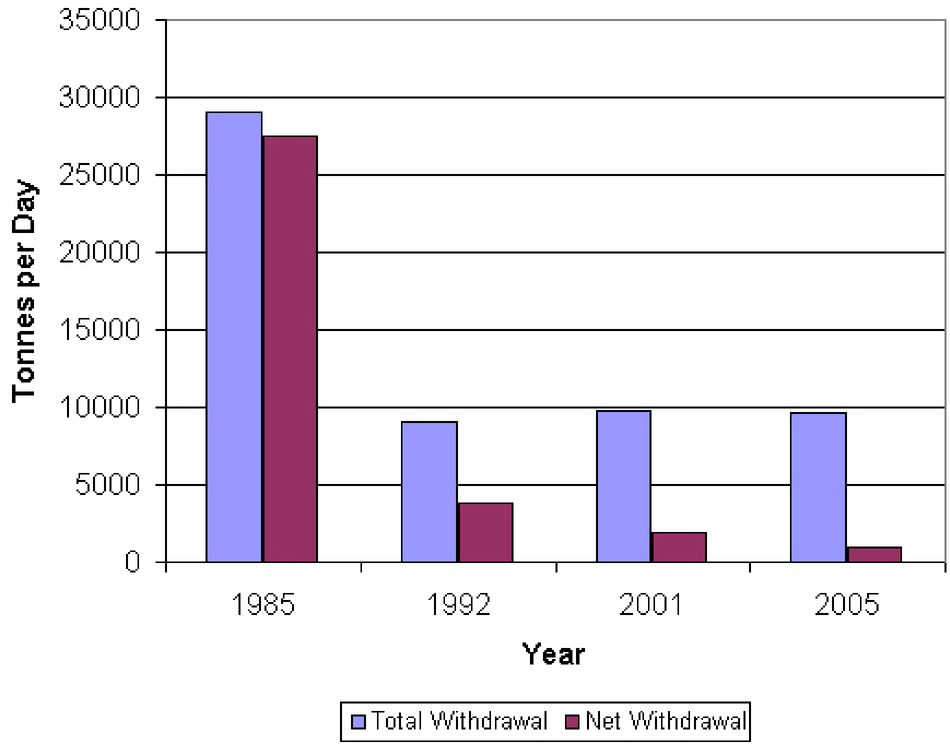

Figure 7.4 Total and net withdrawal for the periods, 1985, 1992, 2001, 2005.

7.8 Distribution of Withdrawal

Table 7.4 and Figure 7.5 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.

2005 figures indicate that domestic withdrawal has dropped slightly to 22 percent. As discussed above, changes in the domestic sector have been static whereas there has been some increase in commercial activity. This is consistent with the results shown in the decrease in domestic well ownership.

Table 7.4 Distribution of withdrawal in the Rotorua Geothermal Field

Withdrawal	1985	1992	2001	2005
Domestic (%)	48	24	23	22
Commercial (%)	52	76	77	78
Domestic (tonnes per day)	14,000	2,200	2,200	2,100
Commercial (tonnes per day)	15,000	6,900	7,600	7,600

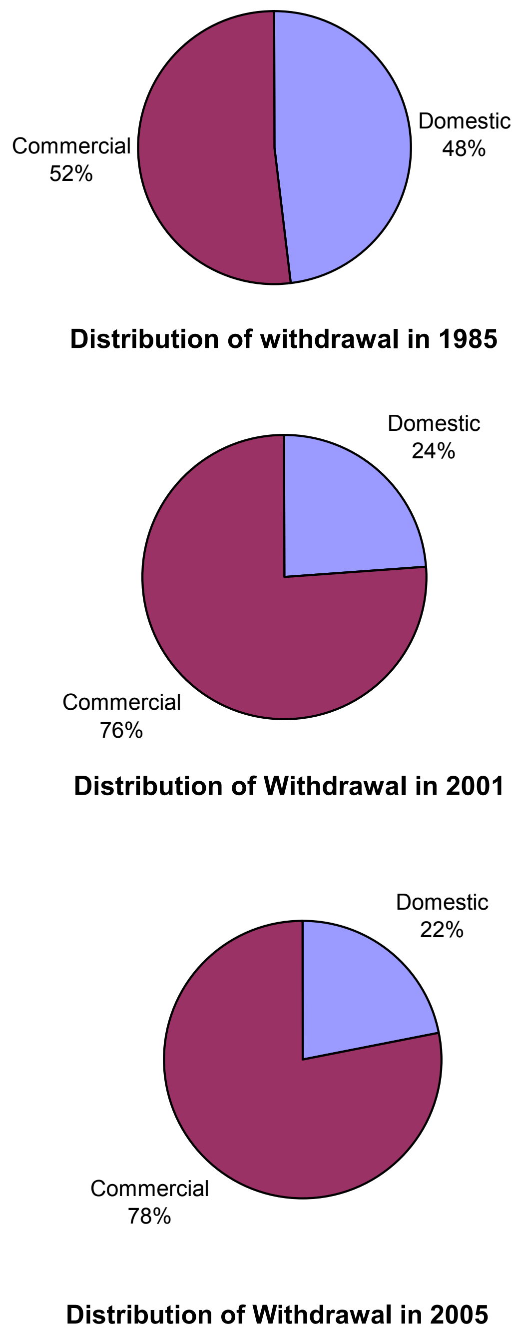

Figure 7.5 Distribution of withdrawal in 2005.

7.9 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 watercourses.

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.

Between 2001 and 2005, eighteen sites moved from soakage disposal to voluntary reinjection and Rotorua Geothermal Regional Plan requirements.

Table 7.5 Geothermal waste disposal in the Rotorua Geothermal Field between 1985 and 2001

	1985	1992	2001	2005
Reinjection (tonnes per day)	1,500	5,300	7,500	8730
Non-reinjection (tonnes per day)	27,500	3,800	2,300	970
Reinjection (%)	5	58	76	90
Non-reinjection disposal (%)	95	42	24	10

Table 7.5 and Figure 7.6 demonstrate the increase in the total volume of fluid reinjected between 1985 (estimated 1550 tonnes), 1992 (estimated 5200 tonnes), 2001 (estimated to be 7500 tonnes) and 2005 (estimated to be 8730 tonnes).

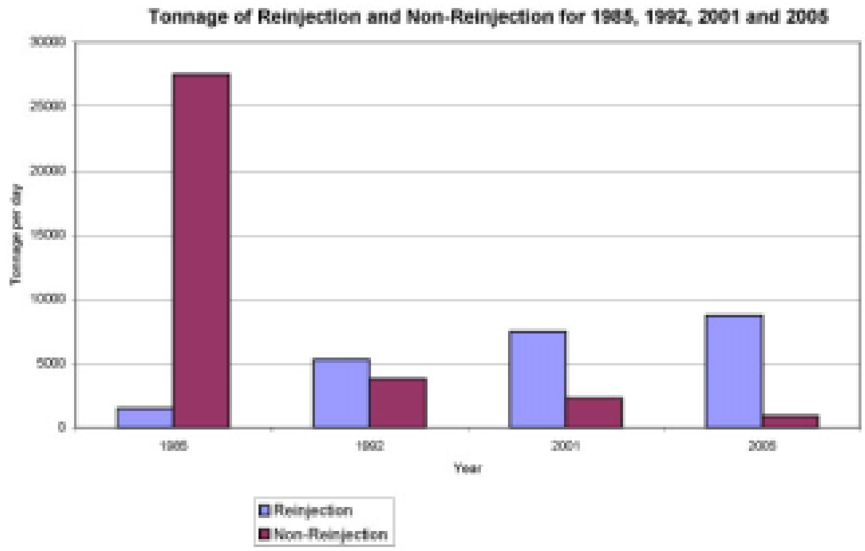

Figure 7.6 Tonnage of reinjection and non-reinjection for 1985, 1992, 2001 and 2005.

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 and finally to 90 percent in 2005 (Figure 7.7). Of the total withdrawal, 620 tonnes per day is permitted to be discharged to surface. Therefore, the actual percentage of fluid able to be reinjected, that is being reinjected, is 96 percent.

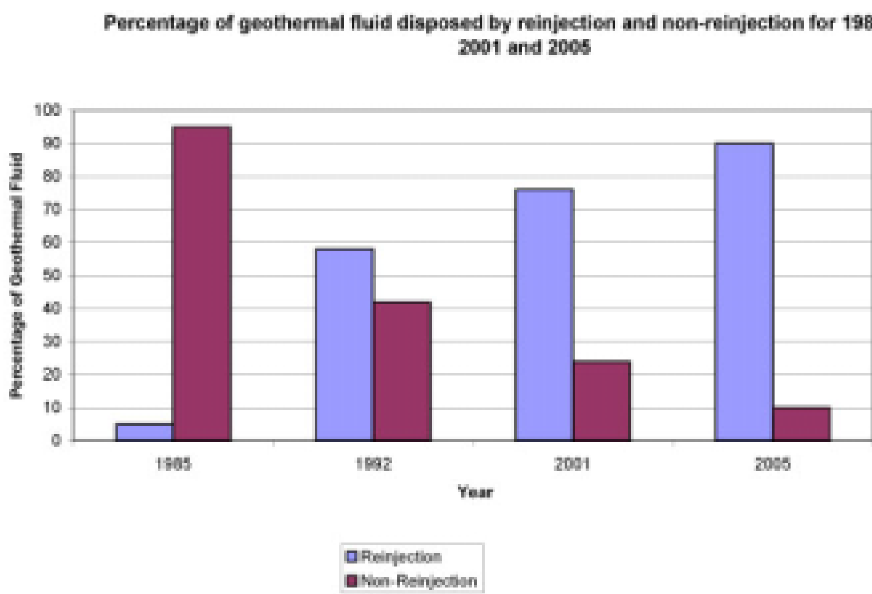

Figure 7.7 Percentage of Geothermal Fluid disposed by reinjection and non-reinjection for 1985, 1992, 2001 and 2005.

There are currently 86 sites using reinjection with the majority operated by commercial users. Some production sites have multiple reinjection bores. Only four known sites remain to move from soakage to reinjection.

7.10 Down Hole Heat Exchangers

There are currently 42 known down hole heat exchangers in use, with the majority (96 %) 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 noted since that time is a result of both surveys within the 1.5 kilometre zone and the need for owners to provide a resource consent at the time of property sale.

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". 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.

7.11 Present 2005 Usage

From the above discussion, the current (2005) usage status of the Rotorua field is summarised in Table 7.6.

Table 7.6 Summary of Geothermal Usage in the Rotorua Geothermal Field as at 2005.

	2005
Total Withdrawal	9,700 tonnes/day
Net Withdrawal	970 tonnes/day
Domestic withdrawal	22 %
Commercial withdrawal	78 %
Number of production sites	140
Number of down hole heat exchangers	42
Percentage wells Domestic	51 %
Percentage wells Commercial	49 %
Reinjection	90 % of total withdrawal
Soakage	4 % of total withdrawal
Surface Disposal	6 % of total withdrawal

7.12 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 slowly rise and domestic use will decline. Total withdrawal is likely to increase slightly and net withdrawal is (following completion of the reinjection programme) expected to fall to by approximately 6 percent. The 6 % is the quantity of fluid currently authorised by resource consent for surface disposal discharged and therefore unavailable for reinjection.

In the past four years, Environment Bay of Plenty has had few 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. Parties now generally understand costs such as ongoing maintenance, cost of replacement bores and compulsory Reinjection as well as the realisation that geothermal can only supply a limited proportion of a domestic households energy needs. The economics of moving to geothermal have, in many people's minds, become extremely marginal.

It is believed that the commercial sector, particularly the accommodation sector will continue to see small growth. Following on from a successful conference in Rotorua on geothermal spa development in 2001, it was suggested that the trend in geothermal tourism would be 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. There has, as yet, been no clear evidence that this trend is occurring on a significant scale.

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 (such as Rydges Rotorua and the Royal Lakeside Resort), which are likely to require proportionally larger quantities of geothermal fluid, will be determined by overseas tourist accommodation trends. This may not increase either, the number of geothermal sites or quantity of fluid extracted. A significant number of the prime locations for future large scale accommodation complexes are already occupied by existing accommodation complexes. It therefore likely that new construction may be at the expense of older structures, as an example of this, the new Ibis Hotel was constructed over a property with existing geothermal fluid allocation. The existing bores a this site were grouted out and the allocation transferred to the neighbouring Royal Lakeside property which now supplies both properties from the one geothermal plant room.

In terms of bore numbers, no large change is expected. It is also expected that domestic bore that fail may not be replaced. Bore that service group heating schemes or commercial properties are more likely to be replaced.

Reinjection at all sites, requiring reinjection is expected to be complete within the year.

Chapter 8: Modelling

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8.1 Introduction

Modelling is a way of describing the physical features of a geothermal system that allows predictions to be made of future behaviour. The first task of the modelling process is to develop a conceptual model that summarises the key features of the geothermal system that control the flow of fluid, energy and chemistry. A conceptual model for the Rotorua Geothermal Field (RGF) has been formulated and refined by many researchers over the years. It is based on all the available information collected from the field by Environment Bay of Plenty, the former Department of Scientific and Industrial Research, and central Government Ministries. In addition, logs from private bores provided valuable geological, pressure and temperature data for the model.

8.2 Development of the Computational Model for the Rotorua Field

The actual computational model is solved by a computer program called a geothermal simulator, which calculates the pressures, temperatures and flows in a geothermal system. The geothermal simulator solves the mathematical equations that describe the physical rules that control the flows of fluid and heat in the porous rocks found in geothermal systems.

Once the model is constructed its output can be calibrated with known field measurements. For example if the rock permeabilities and all the inflows are prescribed, then pressures and temperatures throughout the field can be calculated. These pressures and temperatures are then compared with measured data to evaluate the success of the model. If there is a good match, confidence is gained in the output and the model is deemed acceptable. If the match is poor, it must be adjusted and re-run until it matches all available data. This process is strengthened as the amount of data for calibration increases. This process is illustrated in figure

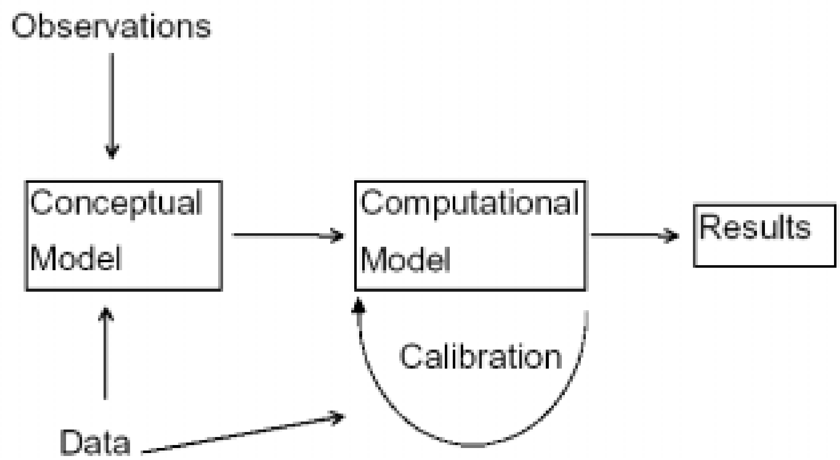

Figure 8.1 Flowchart showing the modelling process.

8.3 The Conceptual Model of Rotorua

Scientific data for the field provides a description of the key processes occurring in the field. For example: water and gas chemistry data provides a description of the processes that water undergoes as it boils, mixes or interacts with particular rock types; and geological and structural information provides the basis for a hydrological model which describes permeability and fluid flow.

Most of the data for Rotorua has been reported in four publications:

- Technical Report of the Geothermal Monitoring Programme 1982-1985;
- Special Issue Rotorua Geothermal Field, Volume 21 No. 1/2 of Geothermics;
- Environment B·O·P Technical Publication No. 7 Rotorua Geothermal Field - Response of the Field since Closure (1987-1992), and
- Environment B·O·P Environmental Report 2001/22 – Rotorua Geothermal Field Management Monitoring.

As well as the information contained in 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 the data that provides the basis for the conceptual model for the Rotorua Geothermal field is described here:

(a) The field is a region of hot water with a horizontal extent of about 20 km^2.

(b) A shallow geothermal aquifer is present to at least 500m, with a strong east-west component in the flow.

(c) The geology is comprised of rhyolite domes in the west, an ignimbrite layer in the east and overlying sediments that are generally impermeable. In the south east there are a number of faults that influence flows.

(d) Surface outflows occur at the Whakarewarewa/Arikikapakapa, Government Gardens/Ngapuna and Kuirau Park/Ohinemutu areas.

(e) Pronounced gradients in chloride, bicarbonate and tritium indicate different near surface fluids in the east and west.

(f) Measurements of the pressure and temperature distribution prior to and after bore closures are generally reasonably well known.

(g) A shallow groundwater aquifer above the field is strongly influenced by lake level and responds very quickly to rainfall.

(h) A general northwards flow of geothermal water discharges into the lake bed.

(i) There are deep upflows of geothermal fluid into the geothermal aquifer beneath Whakarewarewa, and in the north beneath the Pukeroa dome area.

(j) The geothermal water mixes with surrounding cold ground water.

This conceptual model is used as the basis for the computational model. A schematic diagram of the conceptual model is shown in Figure 8.2.

8.4 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. The map (Figure 8.3) used contours to describe the impact of abstraction of geothermal water on the natural outflow of geothermal fluid at Whakarewarewa.

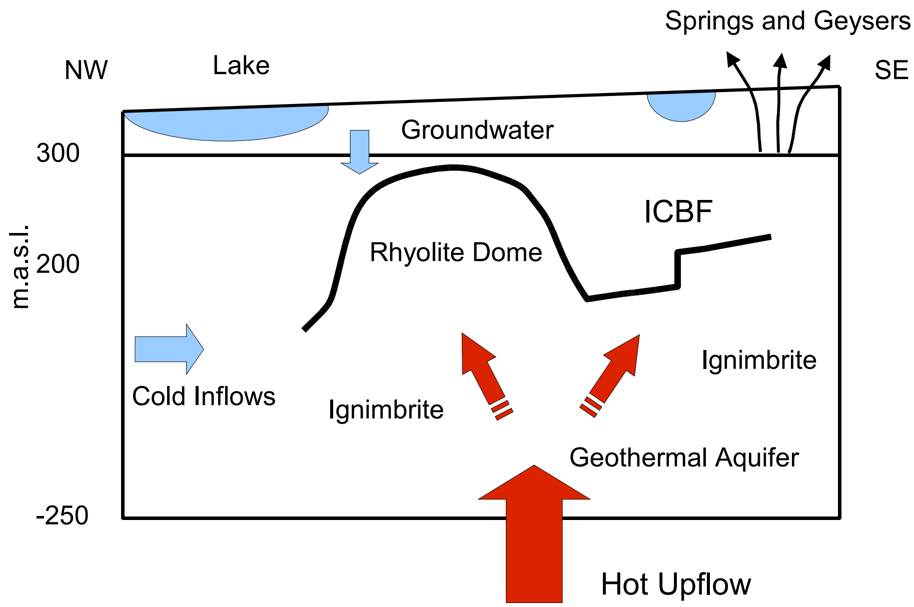

Figure 8.2 Schematic diagram of the conceptual model of flow at Rotorua.

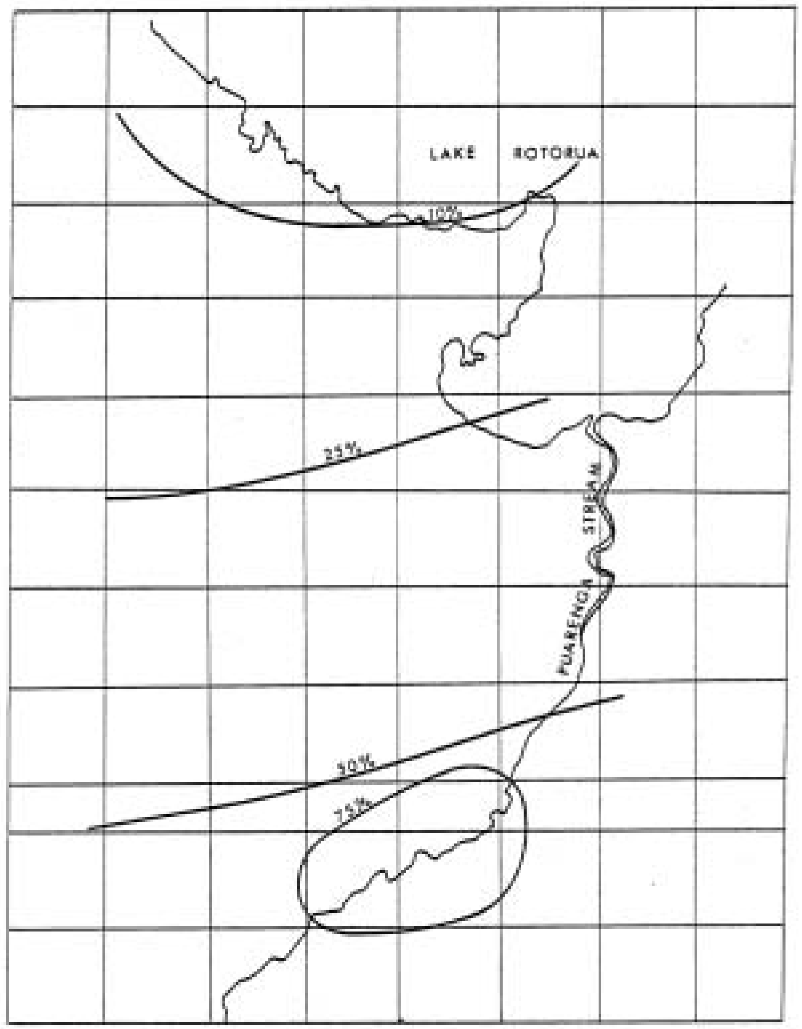

Figure 8.3 Map showing the model impact of withdrawal from the geothermal field on natural flow at Whakarewarewa (from Grant et al. 1985). A Figure of 50% means that withdrawal of 1 tonne/day will reduce outflow at Whakarewarewa by 0.5 tonne/day.

8.4.1 Early Models for the Field

Burnell (1992) developed a numerical description of the shallow geothermal aquifer that 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 agreed generally with the model developed by Grant (1985) and actual geological data by Wood (1985) and geochemical data of Stewart et al (1992).

Burnell and Young (1993) then developed a Three Box Numerical Flow Model that described the outflow areas of the field. This type of model provided 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 which could be brought about by increases in production, closure of bores, or reinjection. The model confirmed generally high permeability, the highly sensitive response of natural flows to changes in reservoir pressure, and the low storage capacity of the system.

A more complex distributed model of the field was developed by Burnell and Young (1993). This model 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 included more detailed spatial variability in an attempt to match changes seen across the field and variations with depth. The objective of this model was 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 simulated coupled transport of liquid, vapour, heat and chloride in a porous medium. The model provided good agreement with measured temperature and pressure data, and changes to outflows at Whakarewarewa and other areas of the field as result of closure program.

8.4.2 **1994 Field Management Plan Model**

The distributed model was used by Burnell and Young (1994) to evaluate the impact of ten field management scenarios using different withdrawal patterns for the field. Using the simulator MULKOM, 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.

8.4.3 **2004 Field Modelling**

In 2004 Environment Bay of Plenty commissioned an update of the 1994 computational model to check model performance against new monitoring data and bring the model for the field into line to current state-of-the-art geothermal modelling practice. Burnell and Kissling (2005) have updated the earlier computational model reported in Burnell and Young (1994). The computational 2004 model has the added advantage compared to previous models because of improvements in computer software and hardware and geothermal modelling practices so that a more complex model has been developed that more accurately represents the conceptual model.

The 2004 model was developed using the TOUGH2 geothermal simulator, developed at Lawrence Berkeley National Laboratory, Pruess (1991). TOUGH2 simulates the coupled transport of liquid, vapour, heat and chloride in a porous medium. The model is a full 3-dimensional reservoir model of the hot aquifer and surrounding groundwater and rainfall recharge is now included in the top layer of the model. The number of grid blocks used in the model has increased. The 1994 model had 462 blocks and the 2004 model has 3550 blocks. The treatment of boundary conditions has also been greatly improved, as reliance is no longer place on pressures along the east and west boundaries. The new model provides a more detailed spatial variability in an attempt to match changes seen across the field and variations with depth. A full description of the 2004 computational model is presented in Burnell and Kissling, (2005).

8.4.4 2004 Model Results

The model is able to provide good agreement with measured temperature and pressure data, changes in pressure since the 1986 Bore Closure Programme and changes to the outflow of Whakarewarewa and Kuirau Park are summarised in Table 8.1 as reported by Burnell and Kissling (2005). Results from this model are presented as contours of pressure (Figure 8.5a), temperature (Figure 8.6a) that can be compared directly with data from Grant at el (1985) and Wood (1985) in Figures 8.5b and 8.6b.

Table 8.1 Match of Model to Measured Data

	Measured	2004 Model
Heat Flow at Whakarewarewa in natural state (MW)	~300	260
Heat Flow at Whakarewarewa in 1985 (MW)	158	176
Heat Flow at Whakarewarewa in 2000 (MW)	>216	245
Mass Flow at Kuirau Park in 1986 (tonnes/day)	0	0
Mass Flow at Kuirau Park in 1993 (tonnes/day)	1,728	1,382
Heat flow at Ngapuna in 1990 (MW)	77	74
Water Level Increase 1986 to 1990 (M)	**(m)**	**(m)**
M1	1.1	1.1
M6	1.6	1.6
M9	2.3	1.7
M12	0.9	0.7
M16	1.9	1.9

Figures 8.7 to 8.11; show the measured water levels of monitor wells through time compared to modelled results. The model shows good agreement to the changes that have occurred from bore Closure in 1986 to 1990 and post bore closure from 1990 to 2004 as summarised in Table 8.2. However, continued increase of the water level at M12 is problematic because the controlling mechanism for the increase is not understood (Burnell and Kissling 2005).

Table 8.2 Comparisons of model and measure water level results from the closure period and post closure period.

	Change between 1986-1990		Change between 1990-2000	
Well	Measured (m)	Modelled (m)	Measured (m)	Modelled (m)
M1	1.1	1.1	0.5	0.4
M6	1.6	1.6	0.4	0.3
M9	2.3	1.7	>0.4	0.7
M12	0.9	0.7	1.0	0.1
M16	1.9	1.9	0.5	0.4

As reported by Burnell and Kissling (2005) some possibilities for the increase are:

1 A seismic event may have opened a fracture under Pukeroa Dome allowing extra upflow to occur in that area;

2 Changes in inflow due to climatic changes;

3 Changes in production or reinjection around M12;

4 Reinjection near M12 may be into a less permeable formation than the underlying rhyolite, and the travel time through that formation is of the order of years rather than days.

The third and fourth possibilities are less likely, since we understand that Environment Bay of Plenty have undertaken a thorough audit of all production and reinjection. Most of the reinjection wells that are used were previously operated as production wells. Consequently most of these wells will have feeds in permeable rock.

The first and second possibilities were tested by, increasing the deep hot upflow under Pukeroa Dome in the model. This was done increasing the upflow by an extra 3,800 tonnes/day from 1996. When this was done the water level in M12 increased at about the right rate as seen in Figure 8.4a. Also, M16 showed a response around 1996, which can also be seen in the data in Figure 8.4b. The explanation for the increase in water levels is also consistent with increases thermal activity observed around the Kuirau Park area and small increases in geothermometer temperatures and chloride concentrations as conclude by Mroczek et al (2003).

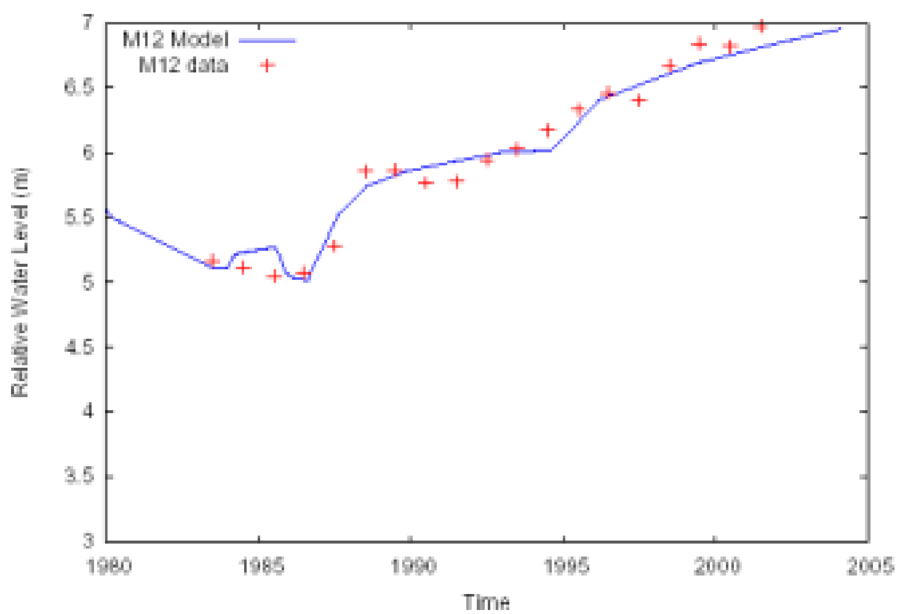

Figure 8.4a Model water levels at M12 if the hot upflow under Pukeroa Dome is increased by 3,800 tonnes/day in 1996.

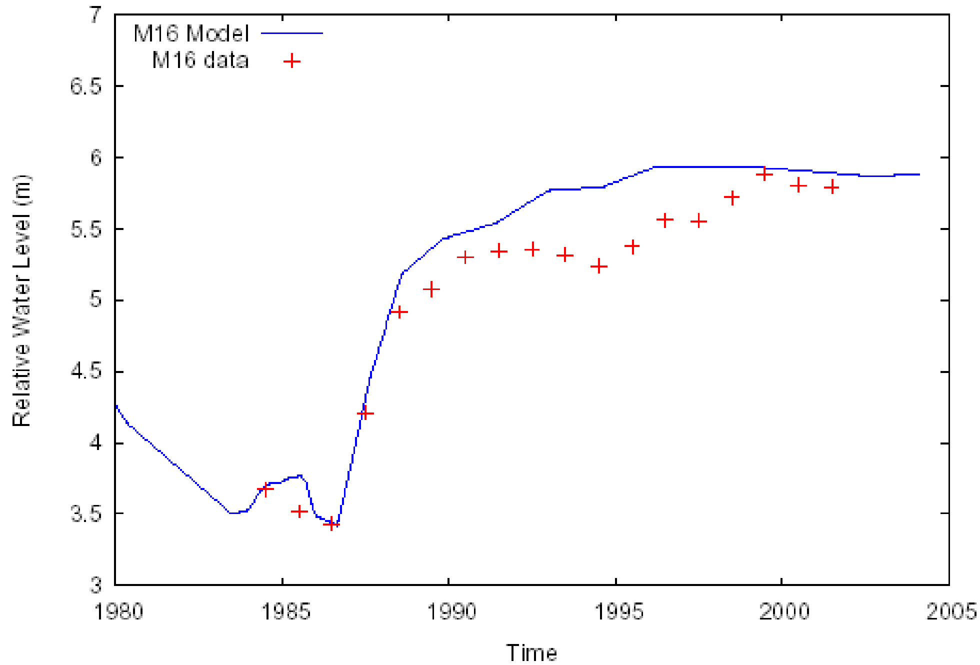

Figure 8.4b Model water levels at M16 if the hot upflow under Pukeroa Dome is increased by 3,800 tonnes/day in 1996.

8.4.5 **2004 Model Discussion**

The new computational model that has been developed for the field has added complexity and provides a better fit to the conceptual model compared to the 1994 model. Overall, the 2004 model provides a good match to monitoring data, including the observed response of the 1986 bore closure programme. The response time of the system to the Bore Closure Programme was about 3 years as observed in the water level monitoring bores. However, the model does not match the observed continued water level response in M12 since1995. Re-running the model with extra inflow into the northern area of the field provided a better fit to M12 monitor well data. This would suggest that there may be additional inflow into the field near Kuirau Park, but the cause of this hypothesised additional inflow cannot be readily identified. Overall, model results show that if production and reinjection is maintained at current levels, then pressures and outflows in the field will continue at current levels. The field now appears to be in a stable dynamic state with small variations in water levels, which are presumably in response to climatic events.

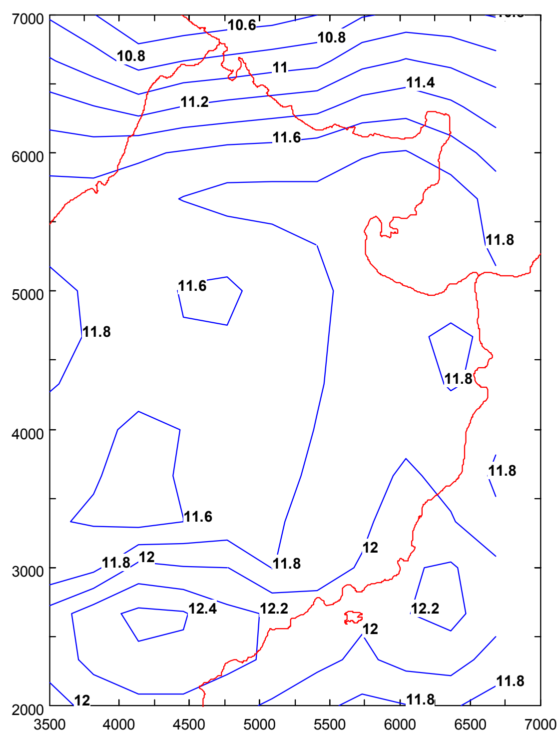

Figure 8.5a Model pressures in 1985 from Burnell and Kissling (2005).

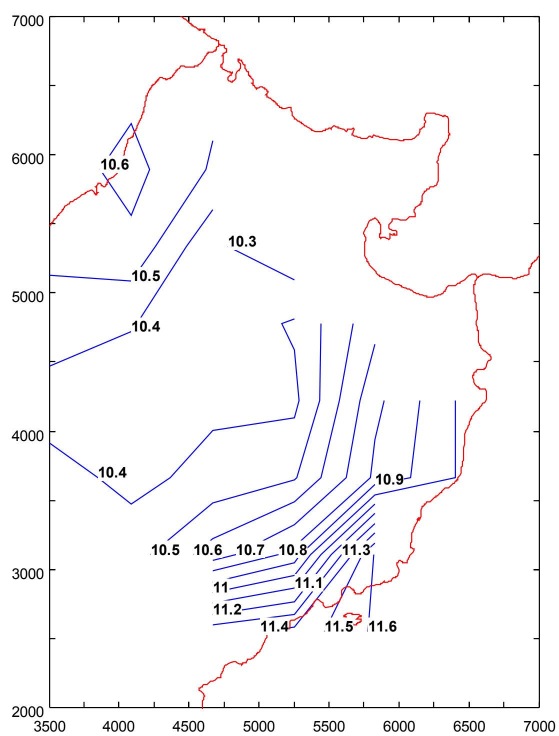

Figure 8.5b Pressures in 1985 inferred by Grant (1985).

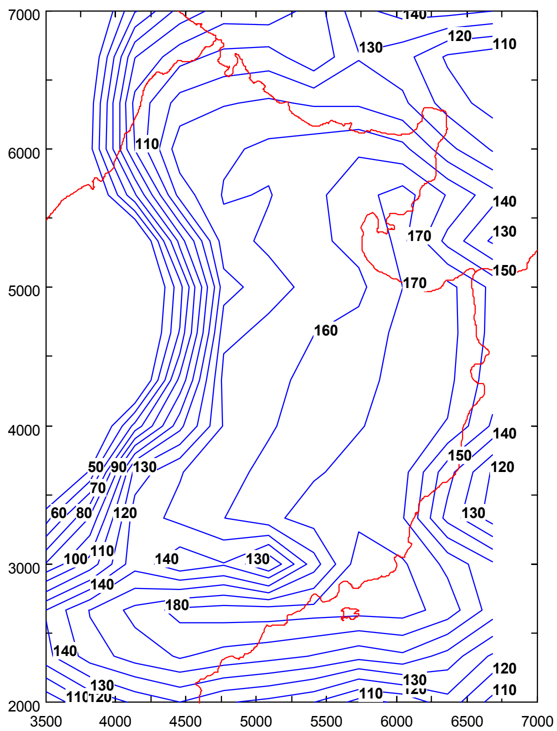

Figure 8.6a Model temperatures in 1985 from Burnell and Kissling (2005).

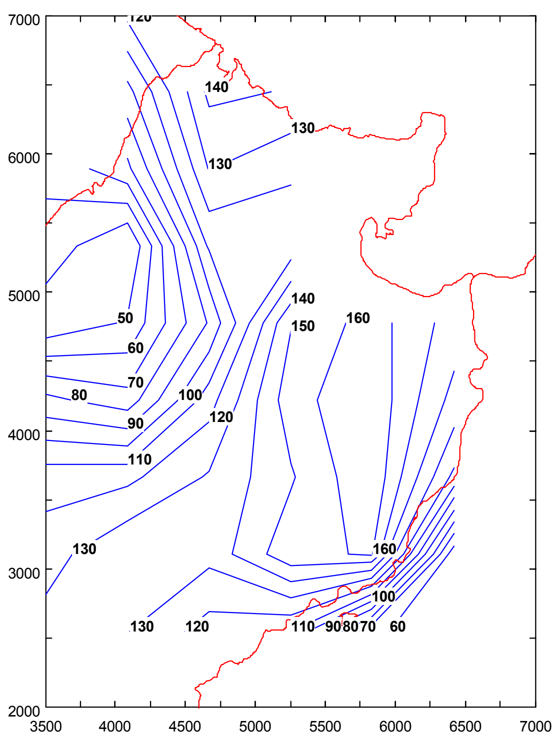

Figure 8.6b Measured temperatures in 1985 from Wood (1985)

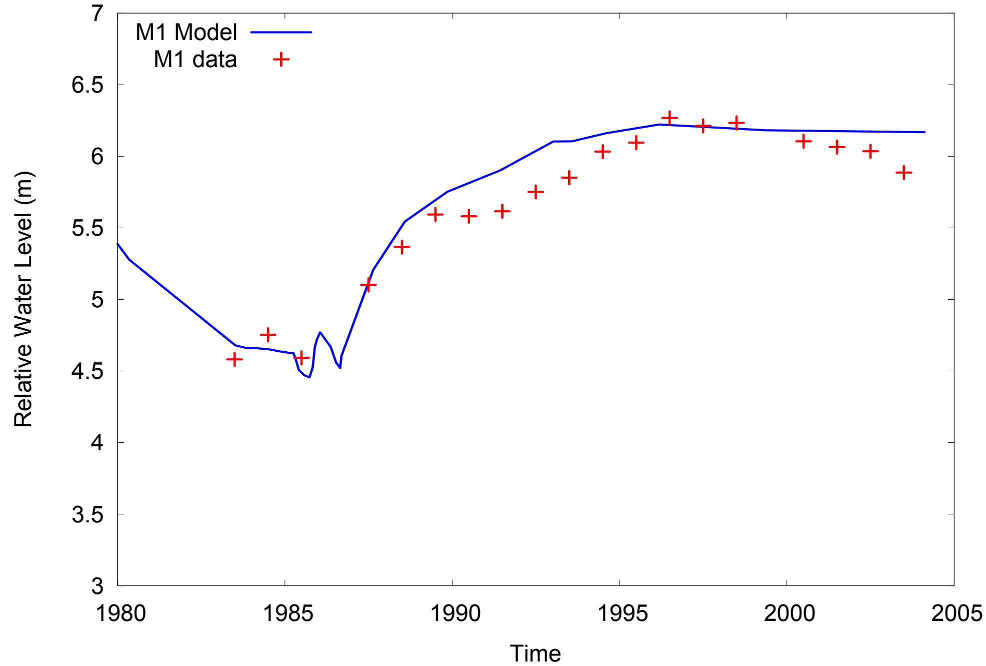

Figure 8.7 Model water levels for M1 from Burnell and Kissling (2005)

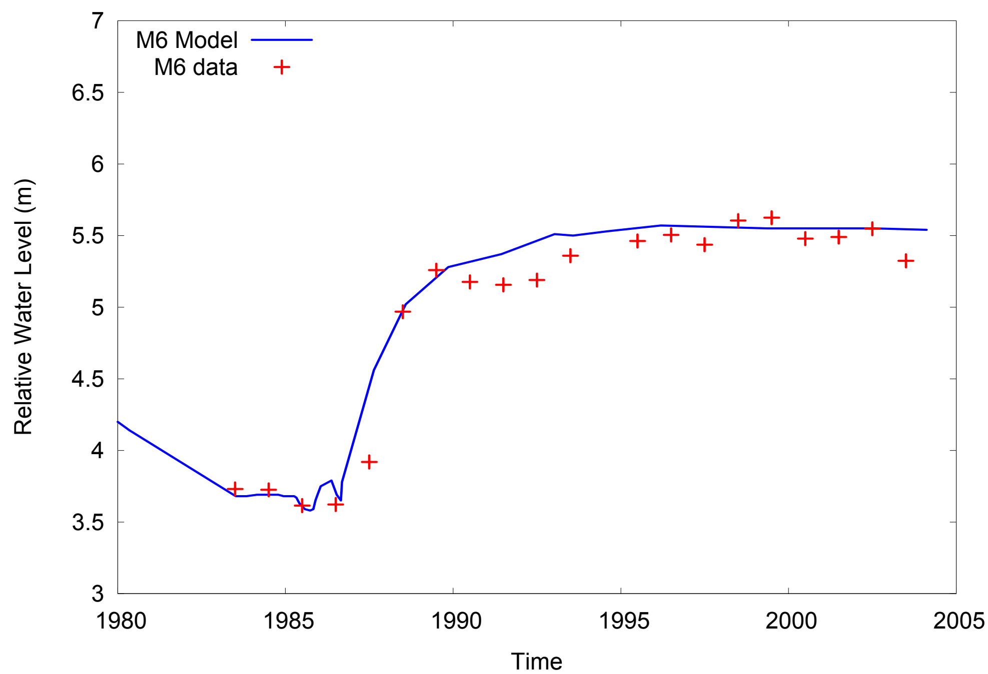

Figure 8.8 Model water levels for M6 from Burnell and Kissling (2005)

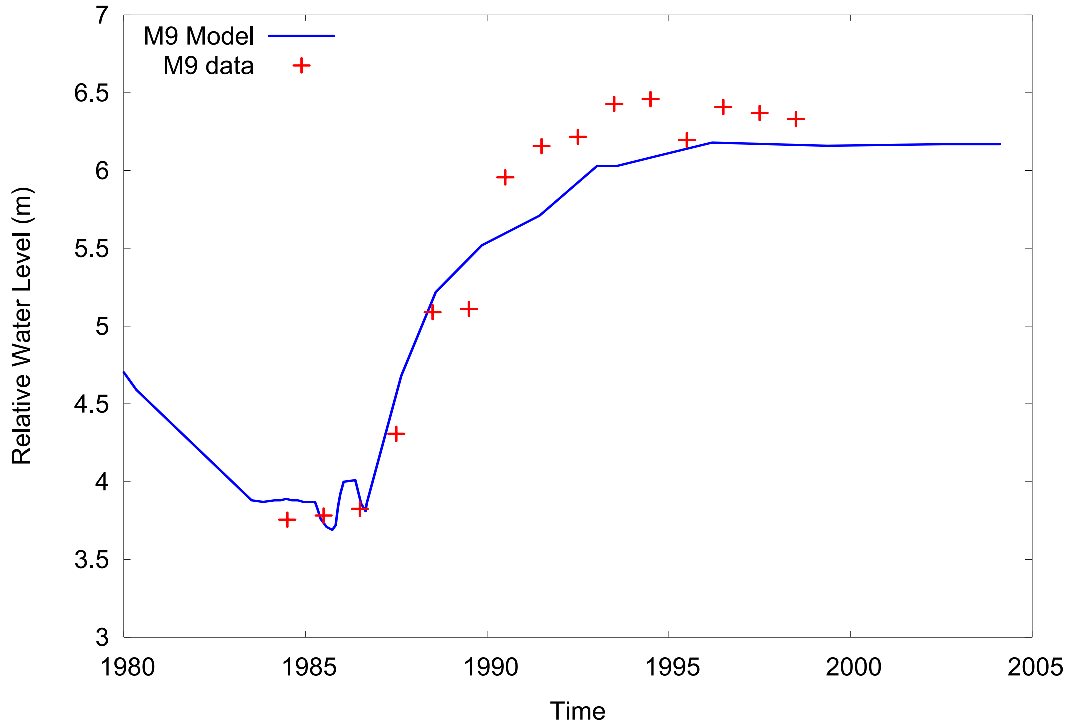

Figure 8.9 Model water levels for M9 from Burnell and Kissling (2005)

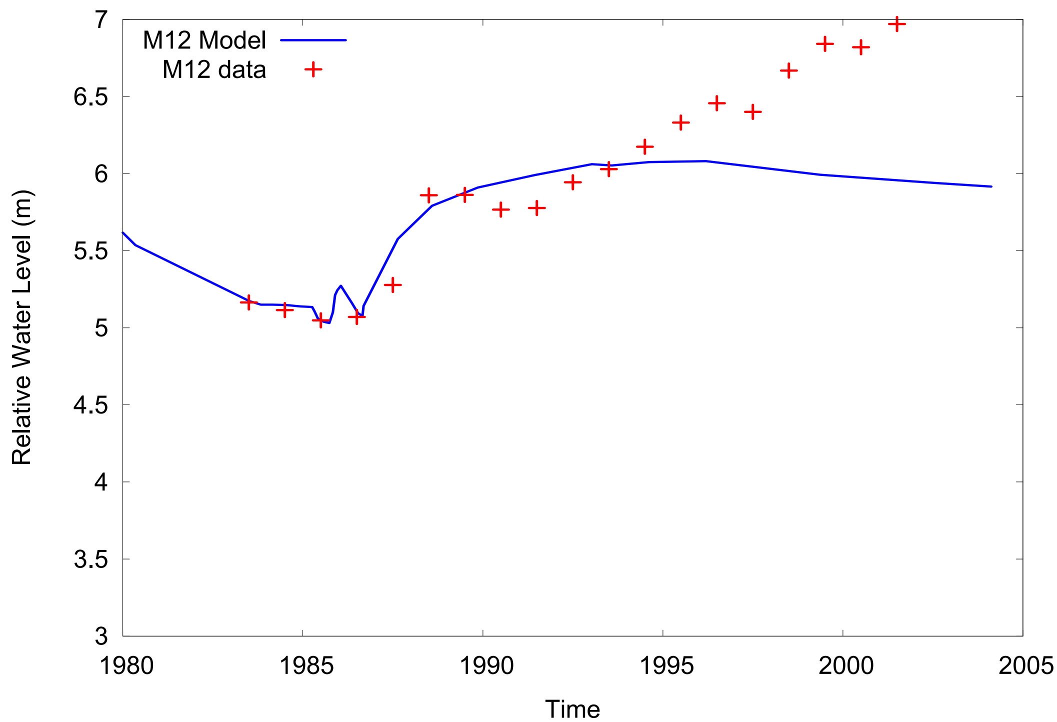

Figure 8.10 Model water levels for M12 from Burnell and Kissling (2005)

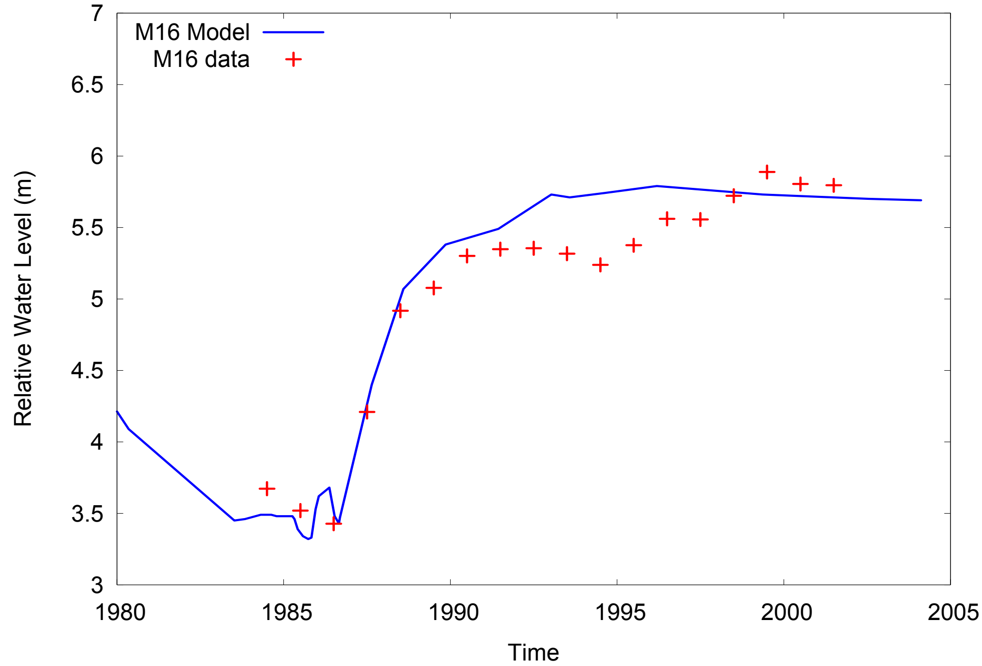

Figure 8.11 Model water levels for M16 from Burnell and Kissling (2005)

8.5 2004 Scenario Modelling

The new model has also been used to quantify the impact of withdrawal scenarios from the field on the natural outflows at Whakarewarewa, Kuirau Park/Ohinemutu and Ngapuna. This information is needed for the pending plan review in July 2005. Burnell (2005) used the 2004 model to evaluate the impact of 19 scenarios for different withdrawal patterns from the field designed by Environment Bay of Plenty. Model scenarios are summarised into 5 groups as shown in Table 8.3.

In the model the mass flow rate of any outflow depends of any outflow upon the pressure and fraction of water present in the fluid and because of reinjection of colder fluid is, occurring into the field the thermal effects of reinjection could also impact on thermal outflow. Therefore, in addition to the mass flow rates and pressure, the temperature and mass of steam was monitored whilst running the model.

Table 8.3 Summarised usage model scenarios.

Scenario Group	Description
1	An increase in production evenly across the field of; 5%, 10% and 20% of the current total abstraction with the 1.5 km exclusion zone in place and full reinjection of the increase.
2	An increase in production of: 5%, 10% and 20% of the current total abstraction with increase located evenly in the CBD and Fenton Street. The 1.5 km exclusion zone is in place and full reinjection of the increased take.
3	Increase existing production evenly across the field until the model indicates a decline in temperature in the thermal outflow areas. The 1.5 km exclusion zone is in place and full reinjection of the increased take.
4	Add new production within the 1.5 km exclusion zone by 5%, 10% and 20% and reducing the exclusion zone to 1.0km, 0.5km and 0km. Increase in abstraction shall be located evenly along Fenton Street and Sophia Street. Full reinjection of the increased production.
5	Increase the use of downhole heat exchangers within the 1.5 km exclusion zone

8.5.1 Scenario Modelling Methodology

Within each group there are a number of sub-scenarios, which increases the total amount of production by 5%, 10% and 20%. The details of all 19 scenarios are presented in Appendix 3. The scenarios were run for 30 years until 2035 and mass outflows predicted by the model were then compared to with present field management of no increase in abstraction. This required the present field management scenario to be modelled to enable a baseline to compare the results of the proposed scenarios. The production scenarios are summarised in Table 8.4.

Table 8.4 Summarised extra production as defined by usage scenarios.

Scenario	Extra Production Tonnes/day	Location	1.5km Zone
1a	500	Existing locations	Yes
1b	1000	Existing locations	Yes
1c	2000	Existing locations	Yes
2a	500	CBD and Fenton St	Yes
2b	1000	CBD and Fenton St	Yes
2c	2000	CBD and Fenton St	Yes
3	250	Existing Locations	Yes
4a	500	Between 1 and 1.5 km	No
4b	500	Between 500m and 1.5 km	No
4c	500	Within the 1.5 km zone	No
4d	1000	Between 1 and1.5 km	No
4e	1000	Between 500m and 1.5 km	No
4f	1000	Within 1.5 km zone	No
4g	2000	Between 1 and1.5 km	No
4h	2000	Between 500m and 1.5 km	No
4i	2000	Within 1.5 km zone	No
5a	320 **kW**	Within 1.5 km zone	N/A
5b	640 **kW**	Within 1.5 km zone	N/A
5c	1,280 **kW**	Within 1.5 km zone	N/A

8.5.2 Scenario Modelling Results

The baseline scenario case after 30 years resulted in a mass flow rate at Whakarewarewa of 29,460 tonnes per day and 1530 tonnes/day at Kuirau Park. The amount of steam under Whakarewarewa between 210 and 250 m.a.s.a.l is 4949 tonnes and temperatures are around 170 ^{o}C and 120 at Kuirau Park.

For each scenario, the results in 2035 were compared to the base case. In particular, comparisons were made with:

- The mass flow rate at Whakarewarewa;
- The mass flow rate at Kuirau Park;
- The amount of steam under Whakarewarewa between elevations 210 and 250 m.a.s.l.;
- Temperatures at Whakarewarewa and Kuirau Park.

The results of the model scenarios are presented in Table 8.5 and Figures 8.12 and 8.13.

Table 8.5 *Model scenarios results. The results are presented as the amount of reduction in outflow from the base case at Whakarewarewa, Kuirau Park, and as the reduction in the mass of steam under Whakarewarewa. A positive number means that the scenario had a reduction compared to the base case and negative number was higher then the base case. Those in highlighted red show scenarios that had significant effects on outflows.*

Scenario	Reduction in outflow at Whakarewarewa		Reduction in outflow at Kuirau (t/day)		Reduction in Steam under Whakarewarewa	
	(t/day)	%	(t/day)	%	tonnes	%
1a	28	0.4	380	**28**	0.2	0
1b	103	**1.3**	684	**50**	0.8	1
1c	295	**3.8**	1,432	**104**	1.7	**2**
2a	30	0.4	477	**35**	0.3	0
2b	94	1.2	869	**63**	1	1
2c	452	**5.8**	1,987	**144**	3.9	**4**
3	7	0.1	235	**17**	0	0
4a	29	0.4	7	1	0.8	1
4b	10	0.1	7	1	1.7	**2**
4c	**-8**	-0.1	10	1	26	**26**
4d	65	0.8	18	1	2.2	**2**
4e	41	0.5	18	1	4	**4**
4f	**-20**	-0.3	23	**2**	36	**36**
4g	143	1.8	38	**3**	4.7	**5**
4h	90	1.2	39	**3**	9.3	**9**
4i	**-50**	-0.6	59	**4**	309	**309**
5a	1	0	0	0	0.2	0
5b	0	0	1	0	0.5	1
5c	7	0.1	4	0	0.8	1

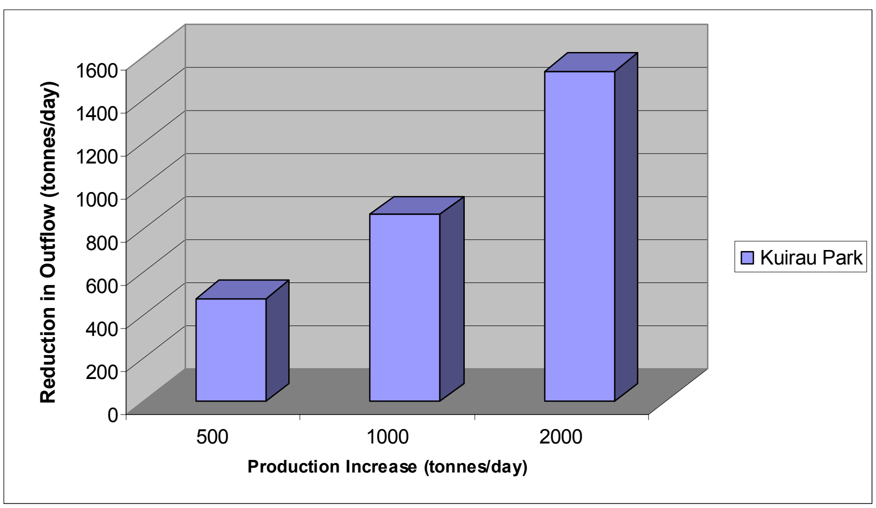

Figure 8.12 *Scenario modelling results showing the reduction in outflow at Kuirau Park as a result of increased production and reinjection. The modelled recovery in outflow at Kuirau Park from 1986 to 1990 was 1,380 tonnes/day.*

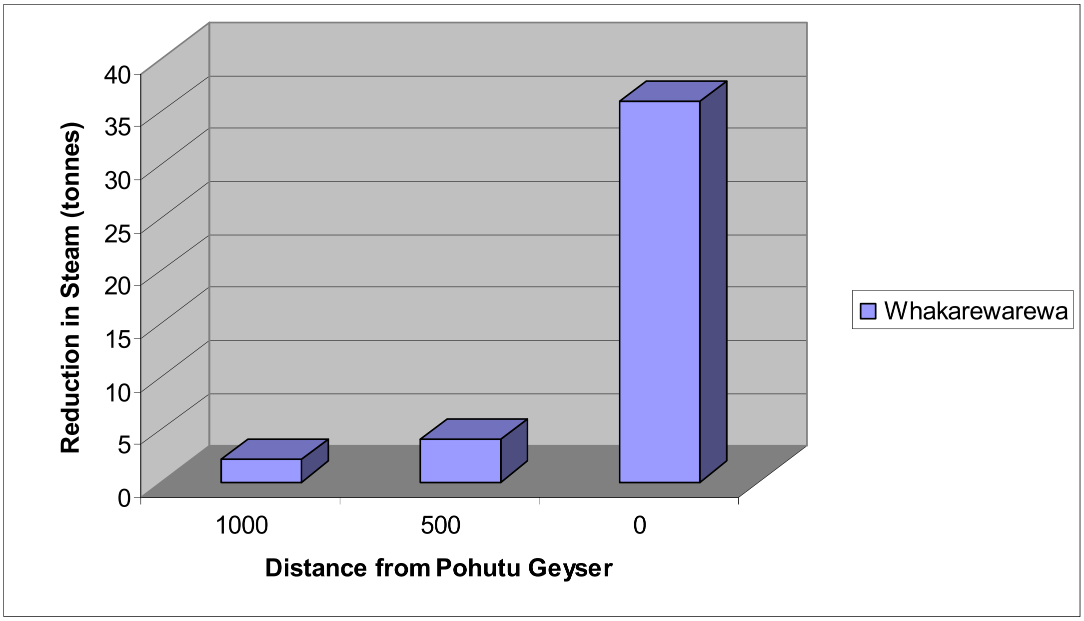

Figure 8.13 Scenario modelling results showing the reduction in steam under Whakarewarewa as a result of increased production and reinjection, allowing production in the 1.5 km exclusion zone at different distances from Pohutu Geyser. The modelled increase in steam under Whakarewarewa from 1986 to 1990 was 100 tonnes.

8.5.3 Scenario Modelling Discussion

The scenario model results presented here are only indicative and only shows the response to the specific pattern of production and reinjection used in the model. However, the results do show the magnitude of the impact that can be expected from the various scenarios.

To assist in the assessment of the impact of these scenarios it is useful to consider the benchmark provided by the response to the 1986 Bore Closure Program. Any scenario that has an impact that is a significant fraction of that measured response is likely to be unacceptable. Relevant aspects of the response from 1986 to 1990 as calculated from the model are:

- The mass flow rate at Whakarewarewa increased by 7,780 tonnes/day;
- The mass flow rate at Kuirau Park increased by 1,380 tonnes/day.
- The amount of steam under Whakarewarewa increased by 100 tonnes.

Scenarios 1 and 2 show a significant impact on the mass flow rate at Kuirau Park. In these scenarios the production is sited in the Rotorua Rhyolite. Because this formation is highly permeable, pressures travel rapidly through the formation to the Kuirau Park area. For Scenario 1, the impact is approximately 70%, that is every 100 tonnes/day of production reduces the outflow at Kuirau Park by approximately 70 tonnes/day. The impact for Scenario 2 is even higher.

On the other hand, the impact of Scenarios 1 and 2 on Whakarewarewa is negligible, except for Scenarios 1c and 2c where the increase in total production is 20%. Scenario 2c reduces the outflow at Whakarewarewa by 452 tonnes/day and the amount of steam under Whakarewarewa by 3.9 tonnes. This impact is nearly 5% of the recovery after 1986. Scenario 3 shows that even a modest increase in production of 2.5% can have a noticeable impact at Kuirau Park.

The results of Scenario 4 are a little more complicated. Scenarios 4a, 4b and 4d have only a minor impact on the surface activity. The other scenarios in the Scenario 4 series have an impact on the amount of steam under Whakarewarewa.

In Scenarios 4a and 4d new production is added to a zone between 1 km and 1.5 km from Pohutu Geyser. The new production is sufficiently distance from Whakarewarewa and Kuirau Park that reinjection lessens any possible pressure drop, consequently the impact on the mass flow rates is small.

In Scenarios 4b, 4e and 4h production is also added to zone between 500m and 1 km from Pohutu Geyser. These scenarios show a slightly smaller impact on the outflow at Whakarewarewa than the corresponding Scenarios 4a, 4d and 4g. The reason for this is that thermal effects are starting to become important. The reinjected fluid is about 25ºC colder than the reservoir fluid, so cooling starts to occur and the steam starts to condense. With less steam present, liquid is able to travel more easily and this counters the reduction in outflow from increased production.

A similar phenomenon is observed with scenarios 4c, 4f and 4i. In these scenarios, reinjection occurs very close to Whakarewarewa and consequently has a significant impact on the steam under Whakarewarewa. In Scenario 4i, 120 tonnes/day of 145ºC is reinjected next to Whakarewarewa, and temperatures fall by 2.5ºC and the amount of steam is reduced by 309 tonnes.

The results show that many of the Scenario 4 series impact on the amount of steam under Whakarewarewa. Exactly what this means for the surface features is unclear at this stage. Many of the features at Whakarewarewa are not steam features, so reducing the amount of steam will not directly affect these features. However, a change in the amount of steam under Whakarewarewa shows that the character of the fluid is changing and if the change is large enough the impact on the surface features could be significant.

The final scenarios, 5a, 5b and 5c, show a negligible impact on the surface features. These scenarios increase the use of downhole heat exchangers by up to 1.28 MW. By contrast the amount of heat extracted for Scenario 4i is approximately 7 MW.

8.5.4 Scenario Modelling Conclusions

(a) 19 scenarios were simulated using the 2004 reservoir Model. The results of these simulations were used to assess the impact on the surface features at Rotorua. The impact was assessed by considering mass flows at Whakarewarewa and Kuirau Park and the amount of steam under Whakarewarewa.

(b) Scenarios with production outside the 1.5 km Exclusion Zone showed an impact on the outflow at Kuirau Park of more than 15% of the recovery from 1986 to 1990.

(c) Scenarios with production and reinjection within 1 km of Pohutu Geyser showed an adverse impact on the amount of steam under Whakarewarewa.

(d) Adding new production and reinjection at a level of 5% of the existing total production to a zone between 1 km and 1.5 km from Pohutu Geyser has only an impact on surface activity of less than 1% of the recovery from 1986 to 1990.

(e) Increasing the use of downhole heat exchangers by up to 200% within the 1.5 km exclusion zone has a negligible impact on surface activity.

(f) The scenarios considered here provide an indication of the likely response to increased production in various parts of the field. If changes to the Rotorua Geothermal Plan are envisaged then a more detailed set of scenarios should be developed and simulated to fully test the consequences of the anticipated change in the production pattern including the combined effects of scenarios presented here.

8.6 Conclusions

(a) The new (2004) computational model for the field has added complexity and provides a better fit to the conceptual model compared to the 1994 model.

(b) The 2004 model provides a good match to monitoring data, including the observed response of the 1986 bore closure programme.

(c) However, the model does not match the observed continued water level response in M12 since1995. Re-running the model with extra inflow into the northern area of the field, provided a better fit to M12 monitor well data. This would suggest that there may be additional inflow into the field near Kuirau Park, but the cause of this hypothesised additional inflow cannot be readily identified.

(d) The model results show that if production and reinjection is maintained at current levels, then pressures and outflows in the field will continue at current levels. In general, the field now appears to be in a stable dynamic state.

(e) 19 scenarios were simulated using the 2004 Reservoir Model. The results of these simulations were used to assess the impact on the surface features at Rotorua. The impact was assessed by considering mass flows at Whakarewarewa and Kuirau Park and the amount of steam under Whakarewarewa.

(f) Scenarios with production outside the 1.5 km Exclusion Zone showed an impact on the outflow at Kuirau Park of more than 15% of the recovery from 1986 to 1990.

(g) Scenarios with production and reinjection within 1 km of Pohutu Geyser showed an adverse impact on the amount of steam under Whakarewarewa. Adding new production and reinjection at a level of 5% of the existing total production to a zone between 1 km and 1.5 km from Pohutu Geyser has only an impact on surface activity of less than 1% of the recovery from 1986 to 1990.

(h) Increasing the use of downhole heat exchangers by up to 200% within the 1.5 km exclusion zone was found to have a negligible impact on surface activity.

(i) The scenarios considered here provide an indication of the likely response to increased production in various parts of the field. If changes to the Rotorua Geothermal Plan are envisaged then a more detailed set of scenarios should be developed and simulated to fully test the consequences of the anticipated change in the production pattern including the combined effects of scenarios presented here.

8.7 References

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Chapter 9: Summary and Conclusions

D A Gordon, Environment Bay of Plenty, Whakatane

This report presents results of the monitoring information and technical investigations undertaken by Environment Bay of Plenty since 2001. The report provides a summary of monitoring and technical information on the current status of the Rotorua Geothermal Field (RGF). This information will assist the review of the Operative Regional Management Plan for the field commencing July 2005.

Most of the geothermal aquifer monitor bores (M – series) for the field have shown water levels increases of 0.5 m from 1992-1999. This cannot be accounted for by variations in rainfall, but may possibly be caused by changes in usage, which occurred subsequent to the bore closures. From 1999 to 2004 water levels in monitor bores have been variable. The water level in M12 continues to increase at approximately the same rate as previously, and is now about 1.5 m above its 1992 level and there is presently no explanation for this. M1 and M24 show drops in mean level of approximately 0.5 m since 1999. For M1 this may be explained by changes in usage patterns in the Rotorua CBD, but M24, being closer to Whakarewarewa (within the 1.5 km exclusion zone) is more difficult to understand. M6 and M16 have had approximately constant levels over this period. The water levels in these bores, although showing significant short time variations, are consistent with the geothermal aquifer pressures having reached equilibrium.

Temperature profile monitoring shows 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 1m of water level change that has been observed from 1992 to 1998).

The recovery of surface features has been a lot slower than the apparent immediate response of aquifer pressure after bore closure. However, from 1992 – 2001 was the greatest period of surface feature recovery with the sudden reactivation of surface features in the northern field (Kuirau Park) in 1998. In the southern part of the field recovery has been mixed. Several features show positive changes, increased flows and temperatures. The primary geysers are erupting for longer periods, while some adjacent geysers have stopped erupting. The results of recent chemical sampling show a similar variation of positive and negative changes.

As the field extraction/reinjection has being relatively steady since 2001, with a slight increase in reinjection it is likely that many of the surface features are now displaying aspects of their natural variability. Across the field there has been recovery, but it is not consistent.

Features that responded quickly to the bore closures have not always remained hot or flowing. Many features have been slow to show responses to the aquifer recovery. A possible explanation for the non-recovery of some features is that hydrothermal alteration processes may have damaged the feeder conduit systems.

Recent geochemical studies of selected surface features and bores was undertaken to compare the results to historical data and provide an overall assessment to highlight any changes (Mroczek et al., 2002; 2003). The chemical evidence shows that the fluids discharged in the northern area of the field at Kuirau Park now match those discharging in the early 1960s and it is likely that this part of the field is near full recovery. At Whakarewarewa springs do not appear to be fed directly by a primary upflow and consequently the recovery has been mixed due to the influence of the hydrology between the upflow and the surface outlets. However recovery has been particularly notable at Parekohoru and Pohutu, but also evident for Okianga Geyser, Ngararatuatara and THC Blowout, with increases in aquifer (geothermometer) temperatures and a greater proportion of deep geothermal fluid being discharged.

The withdrawal of fluid from the shallow aquifers during the exploitation phase did not change significantly the composition or chemistry of the deep aquifer fluid. The shallow aquifer feeding the bores over the last decade shows relatively minor changes in reservoir chloride and small increases in heat (~16^oC). This indicates stability and no deleterious processes are affecting the field.

A CO_2 soil gas survey for the field was carried out in 2003 and results of this work concur with previous surveys for the field in 1992. The highest CO_2 emissions are associated with know areas of surface geothermal activity. The highest fluxes were measured in the Ngapuna area suggesting that upflow into this area is the primary upflow. This conclusion is consistent with the reported fluid chemistry. The greatest extents of degassing areas were observed in known geothermal areas but elevated levels of soil CO_2 flux were also observed in isolated patches throughout the field. These isolated patches do not seem to have any particular spatial arrangement, but are consistent with the existence of high gas concentrations associated with bores.

Usage patterns in the field have continued to remain stable. Total withdrawal and bore numbers have remained relatively static between 2001 and 2005. Non reinjection production now only represents 10% of the total withdrawal. This increase is a result of an increase in reinjection from 7500 tonnes (estimated) in 2001 to 8730 tonnes (estimated) in 2005. The percent of total withdrawal discharged to soakage is now only 4 percent. This means that in 2005 only, 350 tonnes of geothermal fluid still requires reinjection, compared to the 27,500 tonnes that was required to be reinjected in 1985. It is expected that the remaining 350 tonnes of reinjection will be achieved within next year.

In 2004 Environment Bay of Plenty commissioned an update of the 1994 computational model to check model performance against new monitoring data and bring model for the field into line to current state-of-the-art geothermal modelling practice. The 2004 model provides a good match to monitoring data, including the observed response of the 1986 bore closure programme. However, the model does not match the observed continued water level response in M12 since 1995. Re-running the model with extra inflow into the northern area of the field, provided a better fit to M12 monitor well data. This would suggest that there may be additional inflow into the field near Kuirau Park, but the cause of this hypothesised additional inflow cannot be readily identified.

The model results show that if production and reinjection is maintained at current levels, then pressures and outflows in the field will continue at current levels. In general, the field now appears to be in a stable dynamic state.

Nineteen scenarios were simulated using the 2004 reservoir model. The results of these simulations were used to assess the impact on the surface features at Rotorua. The impact was assessed by considering mass flows at Whakarewarewa and Kuirau Park and the amount of steam under Whakarewarewa. Scenarios with production outside the 1.5 km Exclusion Zone showed an impact on the outflow at Kuirau Park of more than 15% of the recovery from 1986 to 1990.

Scenarios with production and reinjection within 1 km of Pohutu Geyser showed an adverse impact on the amount of steam under Whakarewarewa. Adding new production and reinjection at a level 5% of the existing total production to a zone between 1 km and 1.5 km from Pohutu Geyser is assessed has having has only an impact on surface activity of less than 1% of the recovery from 1986 to 1990. Increasing the use of downhole heat exchangers by up to 200% within the 1.5 km exclusion zone was found to have a negligible impact on surface activity.

The scenarios considered here provide an indication of the likely response to increased production in various parts of the field. If changes to the Rotorua Geothermal Plan are envisaged then a more detailed set of scenarios should be developed and simulated to fully test the consequences of the anticipated change in the production pattern including the combined effects of scenarios presented here.

Appendices

Appendix 1– Diary of unusual thermal activity in the Rotorua Geothermal Field

Appendix 2 – Individual Spring and bore commentary for chemistry samples collected in 2002-2003

Appendix 3 – Model Scenarios

Appendix 1: Diary of Unusual Activity in the Rotorua Geothermal Field

1 Whakarewarewa:

Feb 2002 – Spring S506 in Whakarewarewa now killing shrubs around it, with explosive geysering (P c. 2 mins); steam plume conspicuous from distance. Not known for such noisy strong boiling here before.

In Feb 03, Whakarewarewa Village had a collapse into front of the meeting house, hole 2m dia >2.5m deep opened up suddenly under a car. Promptly used for wood rubbish by builders of the new meeting house toilet block!

July 2003 – In Whakarewarewa Village, a new viewing platform has been built and is now in use at N end of Korotiotio to see Pohutu and Geyser Flat. Also a new hole 0.3m dia. has opened up at SE end of Parekohoru, ~5m to SE of its SE end. Hole boils and flows over path. Alongside SW side of footbridge to Oil Baths, a hole ~1.5m dia. blew open on 20/07/03. Muddy waters flooded to <10m radius.

18/03/04 Thursday 18^{th}, a hole 1m dia. and >1.5m deep opened under a house in Whakarewarewa Village. This is house SW from Parekohoru, where office is now located. Hole flared wider at depth. About 10m N of Oil Baths, S305 ~10m dia. Previously boiling strongly and clear, overflowing for several years, had suddenly stopped boiling, its level fell to 1.5m below overflow and went all muddy. In Tarewa Road all springs have now stopped boiling and water levels fallen well below overflows. This includes Parekohoru group.

DP sat 17/04/04 and Wed 21/04/04, articles about road collapses in Whakarewarewa Village. Now 7 have happened in past few years.

24/05/04 Ground collapse hole 1m dia. formed between Parekohoru and Oil Baths and pool all drained down into it.

Wed 15/08/04 sudden water level fall in s327 beside Millie's house. WL fell 1.5m Wed 15th and now explosive boiling. Same day S283 WL fell suddenly 1m and now violent boiling over path, which was closed off.

25/11/04 Ground settlement recently at house by Guide Rangi's grave; has big concrete swimming hot pool built there and soft weak ground has settled.

19/12/04 Sunday night of 19/12/04 big collapse in Rahui central area of outdoor pool. Cracks over 20m dia. And hole 1.5m to boiling muddy water; hole 4-5m dia. This is the once open air bathing pool of the 1890s.

2 Ngapuna

Nov. 2002 Ngapuna bath (Hamiora Place) had black waters and sediments around east end again; not oil or petroleum products (i.e. not human contamination) and probably either sulphide or sulphur?

29/04/03 – Eruption at Ngapuna hangi area on streambank, Tuesday 29/04/03. (DP and NZH Wed 30/04/03). Same site as eruption of 7 March 1996. This latest eruption blew muddy debris <50m high for several hours and a strong westerly wind spread it over houses to east and mud >100m downwind and ~40m wide.

18/01/05 Tuesday evening a big hydrothermal eruption was seen at mouth of the Puarenga stream, seen by MACI guide Mikaere. Big column of muddy waters and rubble went ~30m high for several minutes. Made new crater ~15m dia. and flowing ~3 lps.

3 Kuirau Park

Dec 2002 – In Tarewa Road, eruption of Waiariki Parekaumoana S657 early Dec. not seen but rubble and mud strewn around it. Rocks to 2m distance and muddy flows out into Kuirau Park with grass killed off for 20m to east. Vause put big siphon pipe into Rahopeke to try and fill Down Bath (Hirere) and also covered Ororea S352 in sheets of polystyrene.

Jan 2003 – Ground heating in Kuirau Park north of JC Fountain by Ranolf Street. Tree 46 years old cut down ~35m north of monument as it was now dead and leaning over. Boiling ground around and under tree now.

16/10/03 On Thursday 16th October a hole collapsed underneath a ride-on mower in Kuirau Park. The operator promptly resigned as this has happened three times to him now! This was at site ~40m south of S668. On Thursday 16th a hole beside S668 also blew up in the morning, forming a newly opened crater and throwing debris ~7m high.

Sept –03 Blowout from inside earth bund around s649-653 at 22-24 Tarewa Road. Started weekend of 30/31 August. S647 now boiling strongly 0.3m high and 3 lps across park to east.

Nov 03 In Kuirau park over Tarewa Road side, S647 and S657 both have now stopped boiling and overflowing; conversely Kuirau Lake S601 outflow has increased from 5 to 20 lps and heated. On Thursday 6th November S667 near Ranolf Street and north from JC monument, had a sudden eruption ~15m high.

Jan 2004 Ground collapse occurred in cricket grounds of Kuirau Park. A person fielding for a cricket game fell into a hole of scalding hot water that opened under him; scalded his legs and thighs. Tuesday 27/01/04 a culvert was installed to drain and cover the hole.

Tuesday 10th February 2004 another hole opened underneath the ride-on mower in Kuirau Park, this time east from carpark by children's playground and ~30m NW from footbath by Soda Spring. Hole 1.5m deep to boiling mud, 0.7m dia.

17/03/05 Thurs. 17/03/05 big hydrothermal eruption was seen in north end centre of Ruapeka Bay, Ohinemutu by Trevor Maxwell's wife. Occurred at 1435 hrs and went ~6m high for ~4 minutes. Peter Brownbridge (RDC Inspector) saw eruptions <1m high also on Friday 18th.

4 Bore Failures

In 2001 an area of ~30m diameter alongside well RR1039 in Kuirau Park began boiling and many previously viscous hot mud pools began flowing with alkaline waters. This gradually got worse until the surrounding ground was thumping and trembling and trees were being killed. At the same time RR1039 was lifting sands and continually clogging the heat exchangers in the Aquatic Centre. Downhole investigation of the well confirmed a blockage within the casing and it was then quenched and cement grouted shut. The hot ground nearby then quickly cooled and has remained cold ever since.

05/01/02 At Mr Greene, 50 Sophia Street, his well blowout occurred in the morning of 5th January 2002. This site was ~35m SE of the condemned (geothermal gases and heating) house at 54 Sophia Street. RWD grouted well same afternoon, plus neighbours' wells at 50a and 50b. Greene's well blowout took a lot of cement and had formed a huge cavity underground.

8/8/2002 – Well at Travellers Lodge motel blew out, it had been boiling and sloshing strongly under concrete slabs by street footpath. RWD quenched and grouted an old well 37m deep. The area has remained all cold there since. Note that this well was not on any records or maps anywhere and until this event it was completely unknown.

20/09/02 – Monitor well M16 at Puhi Nui motel in Sala Street discharged itself noisily and flooded around motel; began in night ~1am. It had been standing open until today.

18/10/02 – Old well at ACB Hot Rock backpackers hostel (corner Arawa and Ranolf Streets) blew out ~5pm Friday 18/10/02 and flooded mud and hot waters over driveway and across street. Grouted by RWD. Also Pizza Hut well blew out 2 weeks ago and was grouted shut.

Nov 02 – Well at Kowhai Colonial motel found to be sheared off and offset halfway down in casing at 28m. It was grouted and a replacement drilled. Old well had been lifting sands for about a year before this. Four units had hot ground and floors with ~80 deg C at 1m depths and unusable for past year.

15/06/03 – Well at 85 Whittaker Road blew out (Don Yule's place). Well RR577 beside his house began thumping and spewing hot waters around, with loud noises. Started at 0130 hr Sunday 15th. Well was later grouted shut by RWD who then started drilling a replacement ~15m SW from house. On Tuesday 1st July 2003, at 0400 hrs, a big loud eruption occurred from this new well and the drilling rig fell into a big crater ~12m dia. (DP, Thursday 3/07/03, p.1). By mid July this blowout was finally quenched and the hole filled in after cement grouting of hole.

Saturday 29/05/04 At ~0045 hrs, geothermal well RR534 blew out, emanating muddy waters silt and debris over neighbouring buildings to a radius of ~100m. Police evacuated Havana Motor Lodge motel until ~0400 hrs. Well connected to cold water supply and quenched; it was cement grouted closed a few days later. Well made a terrific noise "like a jet aircraft taking off". (Daily Post, Monday 31/05/04, p.1). Well was drilled in December 1961? to 100m depth and cased to 47.5m. During refurbishment of premises, a paving contractor cut off the old wellhead below ground level and paved over top of it! A week or so later on 29 May 2004 it began violent boiling discharge.

Appendix 2: Individual Spring and Bore Commentary for Chemistry Samples Collected in 2002-2003

Analytical and derived geochemical data may be found in Mroczek et al., 2004.

A2.1 Bores

A2.1.1 Kuirau - Ohinemutu

RR601A

This well is located immediately south of Kuirau Park near the western side of the Rotorua Field. The well is 173 m deep, cased to 134 m with a maximum temperature of 153°C. There has been a small increase in Cl_{res} and H over the last decade but the fluids are still slightly more dilute than in 1983. Na-K and K-Mg geothermometers temperatures have increased slightly, about 10°C. There is no increase in HCO_3 relative to B and Cl and a small increase in sulphate.

RR913

Well RR913 is located within Kuirau, being drilled to 146.5 m (cased 121 m) with a maximum downhole temperature of 152.5°C. There has been small increase in Cl_{res} compared to samples collected in 1986 and there is essentially no change in H. This well used to alternate as a reinjection/production well for the Aquatic Centre but there appears not to have been any significant cooling effect on the aquifer. There are no previous RR913 samples with K analyses, but in the present sample temperatures are higher by about 16°C than the nearby well RR681 which sampled in 1984. The Cl/HCO_3 ratio has halved (2.2 to 1.2) compared to a RR913 sample collected in 1986. The Cl/HCO_3 ratio in well RR681 is about 1.

Little change in the conservative components suggests that the shallow aquifer is similar to that present in the 1980s, expect there is an indication of higher temperature source fluids.

A2.1.2 Government Gardens

RR885

Well RR885 is located in the northern part of the Gardens, near Rachel Spring. It is drilled to 112 m, cased to 68 m. The maximum downhole temperature is 161°C. The 2003 samples are essentially similar in composition to samples collected in 1984-1990. There is some variability, in Cl_{res}, e.g. higher by 30 mg/L than in 1990 but lower by 20 mg/L than in the sample collected in 1989. Only a very small increase in cation geothermometer temperatures (5°C). There is also a small increase in relative amounts of HCO_3 and Cl with respect to B. Compared to the sample collected in 1990, there is an increase in sulphate but the sample is very similar to that collected in 1989.

RR887

This well is located to the southeast, near the lake and Sulphur Bay. It is drilled to 107 m, being cased to 96 m with a maximum temperature of 149°C. There is only a slight decrease in H, but a significant decrease in Cl_{res} compared to samples collected in 1984-89. The difference between the Na-K and K-Mg is instructive in the light of this apparent dilution. The K-Mg geothermometer is essentially unchanged from previous samples, at 185°C for the present analysis, but the Na-K geothermometer has increased by about 14°C to 244°C. Thus although the shallow hydrology may have changed with increased dilution, the deep fluid fraction appears to be hotter. The relative proportions of Cl-B-SO_4 are similar to samples collected in 1984-89 but the present sample contains more bicarbonate.

A new sample was collected in November 2004. Preliminary results indicate an increase in both silica (277 to 292 mg/L) and chloride concentrations (386 to 400 mg/L).

A2.1.3 Ngapuna

M25

M25 is the replacement well for RR889 (M9) being drilled and cased to 245 m, with a maximum downhole temperature of 211°C. Giggenbach and Glover (1992) suggested that all Rotorua waters could be derived from one high chloride parent water with a composition close to that tapped by RR889. Ignoring one "anomalous" high chloride weirbox sample, there has been a small progressive increase in Cl_{res} since 1983 from 1318 mg/L to 1424 mg/L in 2003 but no change in H. Na-K and K-Mg temperatures are essentially unchanged from previous RR889 values (6°C higher). There now appears to be slightly less bicarbonate in the fluids and slightly more sulphate, but these changes are probably well within the natural variations.

A2.1.4 West Rotorua

RR653

This well on the southwestern boundary of the Rotorua Field is drilled to 131 m, and cased to 100 m. A maximum downhole temperature of 141°C is recorded. A small decrease in H (equivalent to 4-7°C) is observed but no change in Cl_{res} since the 1989 sample. Na-K and K-Mg temperatures are lower than measured in 1990 but similar to 1989. The present sample has similar relative proportions of B-Cl-HCO_3 and B-Cl-SO_4 as previous data.

RR738

RR738 is drilled in the central southern part of the field where the rhyolite domes dominate the subsurface geology. A small decrease in H (equivalent to 3°C) and also in Cl_{res} (33 mg/L) is recorded. As in RR887 where there was also a decrease in Cl_{res}, the Na-K temperature has increased by 13°C while K-Mg is essentially unchanged. The relative amount of HCO_3 has also decreased. The absolute concentration of sulphate (92 mg/L) is lower than for the sample collected in 1990 (211 mg/L) but about the same as in 1989.

RR741

Well RR741 is drilled to 130 m, being cased to 104.4 m. A maximum downhole temperature of 123°C has been recorded. This well is located in the central area of the rhyolite aquifer. Both the H and Cl_{res} (16 mg/L lower) are similar as the nearby well RR627 sampled in 1984. Na-K temperatures are higher by 16°C, while K-Mg are similar. The relative proportion of HCO_3 is much lower than in RR627.

RR865

This well is drilled to 105 m (cased to 89.5) with a maximum recorded downhole temperature of 130°C. It is in the central area of the rhyolite aquifers. There is a small decrease in H (equivalent to 3°C) and also in Cl_{res} (23 mg/L), compared to previous samples. Na-K temperature is higher by 11°C and K-Mg is similar to previous values. The relative amount of HCO_3 is lower compared to previous values.

1016

Well 1016 is drilled to 120 m (cased to 91 m) with a maximum downhole temperature of 135°C. Well 1016 is slightly cooler than the nearby well RR638 (~ 8°C) but is less dilute. The Cl_{res} of 130 mg/L is higher than the RR638 samples collected in 1990, but only 22 mg/L higher than in 1989. Cation geothermometer temperatures are similar to RR638. This fluid contains much higher bicarbonate than the nearby well RR638, but a similar proportion of sulphate. Large swings in concentration such as between the 1989 and 1990 samples observed in RR638 (and others discussed above) may reflect local exploitation induced effects.

A2.1.5 Isotopic Analyses

The isotopic concentrations are expressed as δ values with respect to a water standard (V-SMOW), i.e. $\delta^{18}O = [(^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{SMOW} - 1] \times 1000$. $\delta^{2}H$ is defined similarly.

Kuirau Park

Two bores were sampled in the Kuirau Park area. Well RR601A was sampled in July 1983 and Sep 1989, as well as in Jan 2003. The isotopic composition shows very little change over this time. No earlier measurements are available for well RR913, but nearby bores (RR619 and 681) showed similar compositions although cooler water in the 1980s. The Kuirau bores continue the observed pattern of relatively dilute chloride-bicarbonate waters for the area, with temperatures perhaps related to proximity to an upflow.

Government Gardens

Bores RR885 and 887 are in the high bicarbonate (Government Gardens) region. RR885 has slightly more positive δ values than RR680 (sampled in 1989), but the bores have similar temperatures and chloride/bicarbonate concentrations. RR887 was sampled in the 1980s and 2003. The 2003 and 1984 samples are similar, but the 1989 sample again has more negative δ values.

Ngapuna

M25 is in the Ngapuna area, and is compared with the previously sampled nearby well M9. Both tapped high chloride water, representing the least diluted water in the field. This is the only well from the east and south group that was sampled in 2003. M25 has slightly higher $\delta^{18}O$ and chloride, but it is not possible to say if this represents a significant change in time, or simply reflects stable dilution patterns in the area. The latter is more likely.

West Rotorua

Five bores were sampled in this area in 2003. The bores (RR653, 738, 741, 865 and 1016) have increasing $\delta^{18}O$ values, and chloride and bicarbonate concentrations, in this order. Compared with their selected comparison bores, they have similar isotopic and chloride concentrations, but higher bicarbonate concentrations. This would suggests a trend of increasing bicarbonate concentrations in the area, meaning less dilution is occurring of the waters generated deeper in the system by reaction of dissolved CO_2 with rock. However comparison against previously sampled bores, not the nearby bores and reducing the data to atmospheric pressure shows, that for most bores the relative concentrations of bicarbonate are either similar or slightly lower (relative to Cl and B). There is no previous data to compare with well for 1016 where indeed the HCO_3 is much higher than the nearby well. High bicarbonate implies entry of less groundwater from shallow levels from the south (Stewart et al. 1992 demonstrated shallow groundwater entry in this area in the 1980s based on elevated tritium and sulphate concentrations in the waters).

A2.2 Surface Features

A2.2.1 Whakarewarewa Springs

Papakura Geyser (S28)

Historically always active until March 1979 when boiling and geysering stopped. Thereafter, water levels and temperatures declined and this feature shows no recovery. The relative proportion of SO_4 with respect to Cl and B has increased progressively since 1960s, as the temperature and pH have declined. The apparently low geothermometer temperature of 150^oC based on the Mg-Na-K plot is likely to be incorrect (too low) due to an anomalous high magnesium value for the sample collected in 1997. Similarly the extraordinarily high relative concentration of Ca for a sample collected in 1980 is due to incorrect Ca analysis that possibly could be a typographical error in the original data tables.

Ngawharua Spring (S55)

There is essentially no change in the fluids discharged by this spring since the 1980's when the first detailed sampling was made. The latest samples have slightly more absolute Cl and SiO_2 but also more SO_4. The higher Mg suggests equilibration at a lower temperature which is at odds with the observed increase in SiO_2 of 13 ppm, just over the likely uncertainty in the analysis ($\pm$5%). Use of silica concentrations to calculate geothermometer temperature in hot-spring fluids must be interpreted with caution due to the unknown fraction of steam separation during boiling and conductive cooling and possible deposition.

Prince of Wales Feathers Geyser (S72)

Data from this sampling show there is little change between the 1991 and 1997 samples. No data are available pre-1991 to examine longer trends. There is slightly more Cl and relatively more K, perhaps indicative of deeper hotter fluid feeding this geyser, but no increase in SiO_2.

Pohutu Geyser (S75)

There is only one sample with full analysis collected in 1984 that can be compared to the present sample. The relative proportions are similar but there has been a significant increase in absolute concentration of Cl, 549 to 600 ppm and particularly SiO_2, increasing from 374 to 462 ppm. This represents a change from 207^oC to 226^oC in the chalcedony/quartz geothermometer (assuming maximum steam loss), which is a substantial increase. The composition of Pohutu is now very similar to Prince of Wales Feathers, suggesting similar fluids feed both geysers. Cody (1998a) pointed out that features on Geyser Flat (Pohutu, Te Horu, Waikorohihi and Mahanga) previously all had similar waters based on dye tracing experiments by Lloyd (1975). Analyses compiled by Glover (1967), as well as data for the 1984 and 2002 samples are given in Table A2.1 Increasing Cl relative to SO_4 and decreasing Na/K compared to 1984 all indicate deeper-sourced fluids are being erupted by Pohutu. Pohutu now discharges a fluid with compositions comparable to that recorded by Grange in 1937 (as reported by Glover, 1967).

Table A2.1 Analyses of water from Pohutu Geyser, 1937-2002.

Year	Na	K	Cl	SO_4	SiO_2	Na/K	Cl/B	Cl/SO_4
	mg/l							
1937	466	65	600	106	439	7.1		5.6
1955	412	70	579			5.9	108	
1961	485	58.5	560	88	490	8.2	105	6.3
1984	462	56	549	76	374	8.3	102	7.2
2002*	463	61	600	79	462	7.6	115	7.6

***In Mroczek et al. (2002) the results for K and SO_4 were incorrect in this table.**

Te Horu (S76)

The composition of these waters is now very similar to Pohutu and compared to the early 1990s data samples, there have been increases in Cl, cations and silica. The temperature is low (53.7^{o}C) and Gordon et al., (2001) suggest this feature is receiving discharge fluids from Pohutu, which is supported by these results.

Wairoa Geyser (S79)

This geyser has not erupted naturally since 1940, however human induced eruptions did occur during 1958-59. In 1982 the fluid was an acid-chloride mixture of deep and steam heated waters, SO_4 (450 ppm), pH 3, and Cl (442 ppm). In 1987 there was dramatic reversal coincident with local earthquakes, resulting in an inflow of alkaline-chloride fluids (Glover, 1993; Cody, 1998a). This was not sustained and the fluid is now substantially more acidic than the previous sample collected in 1997; SO_4 up from 325 to 1903 ppm, Cl down from 451 to 108 ppm and pH down from 3.4 to 1.7.

Puapua Spring (S81)

The relative proportion of SO_4 has decreased suggesting a greater portion of high chloride deep water is present. In absolute terms the SO_4 concentration is similar to that measured in the early 90's but the Cl and cation concentrations have increased. There is no change in SiO_2. The Cl at 619 ppm is now higher than any sample back to the first collected in 1969 (554 ppm).

Waikite Geyser (S130)

Historically this was the highest discharging feature at Whakarewarewa. Eruptions ceased in 1967 and the vent remained dry until the early 1990s when a collapse allowed fluids to return into the vent. The first sample from this feature was collected in 1996 (Cody, 1998a) and was shown to be acid sulphate fluid, pH 2.3 and SO_4 1760 ppm. The latest sample shows a reduction in SO_4 to 1180 ppm but still negligible chloride at 1.5 ppm that indicates it is still essentially steam heated water.

Kereru Geyser (S278)

Eruptions recommenced at this geyser in 1988, which were the first in over 16 years. The latest sample is very similar to that collected in 1993 which at that time was more concentrated than the average (Glover, 1993).

Korotiotio Spring (S283)

This spring ceased reliable overflow into the Oil Baths in 1978. Since 1996 water levels have gradually risen but overflow has not been established. Between 1982 and 1993 this feature had stable composition and the latest sample is very similar to that collected in 1993. However there has been a slight increase in SO_4, from 59 ppm to 68 ppm and a drop in silica from 350 ppm to 325 ppm. These are relatively minor changes but do suggest less deep geothermal aquifer fluid is present in this spring. Glover (1967) reports a 1878 analysis of 585 ppm Cl and 72 ppm SO_4. This compares with the 2002 sample of 571 ppm Cl and 68 ppm SO_4.

Parekohoru Spring (S284)

Historically this pool has always overflowed but during the winter of 1986 several cessations occurred. By the late 1990s strong overflows and boiling surges were again occurring. Glover (1993) noted that this feature has displayed stable compositions between 1969 and 1993. The 2002 sample shows compositional changes very similar to those observed at Puapua (over 250 m away). There is little change in SO_4 and SiO_2 but there are significant increases in absolute concentrations of Cl (561 pm to 610 ppm), Na, K and HCO_3, that all exceed previous values but the relative proportions do not differ greatly. This is indicative of higher chloride, deeper aquifer fluid reaching the surface now and is consistent with recent increases in spring activity.

Ororea springs (S351, S352)

This group of springs have shown variable activity since the 1930s when they were used to supply the Ward Baths in Rotorua city. This was discontinued after cessation and eruptions between 1938 and 1943. Activity recommenced in 1982 and boiling overflows continued until 1996. Water levels and temperatures are now low, similar to those during a period of low activity (65-85^{o}C) between 1983 and 1986 with reduced chloride and increased sulphate. Between 1987 and 1993 the composition of the Ororea S351 fluids was stable and less dilute than prior to 1987 (Glover, 1993). The latest sample (Ororea S352) is similar to those collected during the 1983-86 low activity period. The change in absolute concentrations since 1993 has been large, Cl decreasing from 835 ppm to 746 ppm and sulphate increasing from 52 ppm to 256 ppm.

Spring 377

This is one of several springs along the western side of Lake Roto-a-Tamaheke, which showed recovery in the 1980s, however in March 2001 boiling and overflowing stopped. In 1983 this spring was a near neutral chloride-sulphate spring (Cl 613 ppm, SO_4 147 ppm) spring at 98^{o}C. The latest sample shows a decline in temperature to 70^{o}C with increasing dilution with steam heated fluids with SO_4 increasing to 250 ppm and chloride declining to 533 ppm. There has also been a drop in silica, 282 ppm to 236 ppm. The compositional changes are consistent with decreased spring activity.

Okianga geyser (S488)

During the 1980s-90s this small geyser erupted about once an hour to about 4 m height. In 1999 many small vents opened in the area and the geyser activity stopped. Compared to samples collected in 1983 and 1984 the latest sample shows dilution in Cl, SO_4 and B but the relative proportions of these components have not altered significantly and the silica concentration is unchanged. However the Na has decreased compared to K, suggesting an increase in temperature of the deeper water component. For the 1983 and 1984 Okianga spring samples the Na/K geothermometer temperatures were 184^{o}C and 183^{o}C respectively, while the 2002 sample now gives a value of 203^{o}C. The isotopic composition suggests this geyser is fed by deep water, which is now more dilute.

Spring 506

This feature was selected for sampling as it represents a small continuously discharging hot chloride feature in the western portion of Whakarewarewa. No previous analyses appear to exist for this feature. It is a hot (90^{o}C) alkaline chloride spring with low sulphate (pH 9.1, Cl 551 ppm, SO_4 73 ppm). The composition is like the way Ngararatuatara (S529) was, and like Korotiotio spring (S283) is now. The cooler aquifer temperatures of S506 and lower bicarbonate indicate different subsurface processes/sources than Ngararatuatara, where it appears the groundwater dilution takes place at a deeper level.

Ngarararatuatara (S529)

This continuously discharging feature has been sampled regularly since 1979 and has shown relatively stable Cl compositions. The latest sample (523 ppm) is similar to the previous sample collected in 1993 (522 ppm). Between 1979 and 1993 the average Cl was 528 ± 9 ppm (24 samples) with a high of 544 ppm measured in 1982 and a low of 512 ppm in 1990. Glover (1967) reports values of 580 ppm and 568 ppm in samples collected in 1937 and 1955 respectively.

However as for the Okianga Geyser, the Na has decreased while K has remained essentially constant. In Ngarararatuatara the geothermometer temperature increase is much smaller, from an average of 248 ± 3°C between late 1984 an 1993 to 257°C in 2002, a value which had not been exceeded since 1984.

THC Blowout (S952)

This feature formed in 1987 as a result of problems with a nearby bore. Between 1991 and 1993 the "blow-out" discharged fluid with a stable concentration higher than any other Whakarewarewa spring (Glover, 1993). The latest sample shows a slight increase in Cl (1024 ppm to 1052 ppm) and lower sulphate (66 ppm to 48 ppm). Again as for Okianga and Ngarararatuatara springs there is a decrease in Na but an increase in K. Between 1988 and 1993 the average Na/K geothermometer temperature was 215 ± 2°C and for the 2002 sample this is now 222°C.

A2.2.2 Ohinemutu-Kuirau

Little Waikite (S1215) and Porahi (S122)

For both Porahi (S122) and Little Waikite (S1215) the Na/K ratios have decreased and this is reflected in the higher geothermometer temperatures. An increased silica in Porahi (286 ppm to 299 ppm) also suggests heating of the shallow aquifer. There is no change in Little Waikite silica concentrations (300 ppm to 301 ppm) but since the last sample collected in 1983, the HCO_3 has increased from 189 to 269 ppm with minor reduction in chloride (330 ppm to 310 ppm). Glover (1967) reports a Little Waikite spring analysis of a sample collected in 1903, which contained 335 ppm Cl and 348 ppm silica

Soda Spring (S624)

Unlike the relatively minor compositional changes at Ohinemutu over the past 20 years, the Kuirau Park features have seen a reversal back from dormancy to discharging acid-chloride fluids and finally in 2002 alkaline chloride fluids. A description of Soda Springs (S624) by Cody (1998b) typifies the behaviour of the springs in the area. In 1953 the spring was at 85°C and discharged a alkaline-chloride fluid (pH 9.3, Cl 370 ppm). By 1982 the temperature and pH had decreased to 41.8°C and 4.5 respectively. Recovery began in 1989 with progressively increasing temperatures and pH, so that by 1997 the temperature was 82.1°C, pH 7.5 and Cl 341 ppm. In 2002 the temperature is 86.6°C, pH 9.1 and Cl 361 ppm. Glover (1967) also reports partial compositions of "Soda Springs" for samples collected in 1888, 1937 and 1955. The historical results are variable (i.e. chlorides were 247 ppm in 1888, 240 ppm in 1937 and 315 ppm in 1955) but lower in Cl, Na and SiO_2 than the 2002 sample.

Tarewa Spring (S653), S657 and Whakaterekohukohu (S722)

Similarly for the Tarewa spring (S653) where the latest sample collected was hotter (91.8°C vs 75°C) and less dilute (Cl 332 ppm vs 308 ppm) than the sample collected in 1963 (Glover, 1967). However the relative proportion of sulphate is still higher and the absolute changes are not as dramatic as for the Soda spring. Spring 657 is also showing substantial recovery when compared to the 1981 sample. Cl has increased from 282 ppm to 326 ppm and SO_4

has reduced from 125 to 70 ppm. Whakaterekohukohu (S722 - J C Fountain area) discharges near boiling alkaline chloride fluid (pH 9, Cl 364) with high silica and low sulphate, with relative proportions of B-Cl-SO4 similar to the 1963 Tarewa spring sample. Except for the higher collection temperature and lower SO_4, the composition of this spring is very similar to the recovered Soda Spring and it is likely that these compositions now represent the typical chemistry of these springs prior to exploitation in this part of the Rotorua geothermal field.

Kuirau Lake Feature (S601)

Kuirau lake is the largest hot spring in this area (5000 m^2) and has shown variable activity, often being a warm (about 45-50°C), acidic, low chloride and not overflowing feature (Scott and Cody, 2000). Since 1988 the lake has reheated (70-80°C) and since December 1997 the outflow has fluctuated between 25 and 50 l/min (Scott and Cody, 2000). Lake samples were collected and analysed in 1945 and 1963 (Glover, 1967), biannually between 1989 and 1993 and once in 1997. The 1989-97 sample compositions are all similar. Selected parameter concentrations and collection temperatures are presented in Table A2.2. This shows that the present lake composition is similar to the earliest 1945 and 1963 samples except that the relative proportion of SO_4 remains high, which is also shown in the Figures. What is very puzzling is the low sample collection temperature, which may be a consequence of the changes in local hydrology due the recent nearby hydrothermal eruptions, however there appears to be no change in chemical composition. The lake was overflowing strongly at the time of sampling and the historically high Cl is not due to evaporation in a stagnant feature.

Table A2.2 Analyses of water from Kuirau Lake, 1945-2002.

Year	t	pH	Na	K	Cl	SO_4	SiO_2
	°C	mg/l					
1945		7.3	339	34	348	97	341
1963	99	7.5	330	31.5	326	45	318
1997	80	7.6	372	36	330	105	330
2002	47.1	7.6	350	32	352	107	304

A2.2.3 Ngapuna and Government Gardens

Rachel Spring

The latest Rachel spring composition is essentially the same as over the period 1990-1993 but slightly more dilute than in 1955 (Glover, 1967). Cl and SO_4 are now 514 ppm and 39 ppm respectively compared to 558 ppm and 84 ppm respectively in 1955.

Postmaster's Bath spring (Matuatonga)

Since the last sample collected in 1983, the Postmaster's Bath (Matuatonga) spring has had a large increase in HCO_3 (477 ppm to 760 ppm) and H_2S (31 to 115 ppm) and a drop in Cl (512 ppm to 472 ppm), SO_4 (71 ppm to 29 ppm) and only a small decrease in SiO_2 (215 ppm to 202 ppm). The spring has also cooled off (94.7°C to 78°C) with an accompanying drop in pH (8.3 to 7.0). With such few samples it is difficult to know how to interpret such changes. The most likely explanation is dilution (mixing) at depth with consequent cooling and suppression of boiling. Dilution by an oxygenated surface groundwater would have resulted in a considerable increase in SO_4. The "bubbling alkaline pool in front of Postmaster Bath" sampled by Grange in 1937 may be the same feature (Glover, 1967). At that time the composition was Cl 568 ppm, SO_4 190 ppm and silica 214 ppm.

Stopbank Spring (S1100) and Hona Baths spring

Of the high chloride springs in the Ngapuna area, there is essentially no change in S940 from the sample collected in 1993, except for an increase in SO_4 (76 ppm to 126 ppm). The Stopbank spring (S1100) appears to be more dilute (Cl 1880 ppm to 1708 ppm) with a slight increase in SO_4. No samples have been previously reported from the Hona Baths but this spring also has high chloride (1617 ppm), approaching that of the Stopbank spring but with significantly more SiO_2 (313 ppm vs 247 ppm) and very low SO_4 (10 ppm). On the day that this spring was sampled it was not overflowing but was observed to be doing so three weeks previously. The low sulphate suggests this feature is not stagnant.

Hamiora Baths spring

The other spring sample collected in this area was from the Hamiora Baths, which are located further east towards the periphery of the geothermal field. The spring waters are dilute compared to the others (Cl 544 ppm) and high in HCO_3 (336 ppm), indicative of groundwater dilution at sufficient depth to suppress boiling and allow the dissolved CO_2 (carbonic acid) to be neutralised to HCO_3 by reaction with country rocks (as for Kuirau). The Cl/B ratio clearly relates this spring to the other Ngapuna features. The more negative isotopic values are consistent with such dilution.

A2.2.4 Isotopic analyses

Isotopic concentrations are expressed as δ values with respect to a water standard (VSMOW), i.e. $\delta^{18}O = [(^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{SMOW} - 1] \times 1000$.

δ^2H is defined similarly.

Whakarewarewa

Ngawharua (S55) shows a slightly higher (less negative) $\delta^{18}O$ and increase in SO_4 since the 1980s indicating extra surface evaporation or steam heating, consistent with the chemical observations. Prince of Wales Feathers and Pohutu geysers have higher $\delta^{18}O$ and chloride supporting chemical indications of higher-temperature, deeper-sourced fluid now feeding these features. Puapua has a significantly lower $\delta^{18}O$ indicating less surface or near-surface evaporation, also shown by less sulphate. The higher chloride and bicarbonate values also indicate greater input of diluted deep water. Kereru has unchanged $\delta^{18}O$. There are no previous analyses for Spring 506. Ngararatuatara has higher $\delta^{18}O$ and slightly higher sulphate suggesting evaporation combined with dilution.

Korotiotio has higher δ18O and sulphate indicating more steam heating/surface evaporation like Ngawharua. Parekohoru has δ18O within the range of previous values, but higher chloride and bicarbonate show greater input of diluted deep water like at Puapua.

Ororea shows increased steam heating even compared with the 1983 sample. Okianga Geyser has higher δ18O but lower chloride and sulphate indicating more groundwater is mixing with boiled deep water to dilute it. THC Blowout accesses deeper water with higher chloride concentrations. The higher $\delta^{18}O$ is consistent with higher chloride, but no earlier results are available for comparison.

Ohinemutu-Kuirau

At Ohinemutu, Porahi has similar isotopic and chemical composition to nearby Little Waikite (S1215) sampled in 1983. Its bicarbonate concentration is higher than in 1983. The Kuirau features had not been sampled before. Their concentrations are similar, but slightly elevated compared to the Ohinemutu samples. S653 and S649 (sampled in 1983 and 1984 at Kuirau) have very similar isotopic values, showing that they are affected by similar processes.

Ngapuna - Government Gardens

Rachel Spring (Whangapapiro) shows remarkably little change compared with the 1984 sample, except for lower sulphate. Its sulphate concentration has been variable in the past. Ngapuna springs have lower chloride and higher sulphate and bicarbonate, with little change in isotopic composition indicating more dilution with steam-heated groundwater.

Appendix 3 Model Scenarios

No.	Scenario
1a	Increase existing production evenly across the field by 5%. This is an increase of 500 tonnes/day. The 1.5 km exclusion zone remains in place and there is full reinjection of the increased production.
1b	Increase existing production evenly across the field by 10%. This is an increase of 1000 tonnes/day. The 1.5 km exclusion zone remains in place and there is full reinjection of the increased production.
1c	Increase existing production evenly across the field by 20%. This is an increase of 2000 tonnes/day. The 1.5 km exclusion zone remains in place and there is full reinjection of the increased production.
2a	Add new production evenly in the CBD and Fenton Street of 5% of the current total. This is an increase of 500 tonnes/day. The 1.5 km exclusion zone remains in place and there is full reinjection of the increased production.
2b	Add new production evenly in the CBD and Fenton Street of 10% of the current total. This is an increase of 1000 tonnes/day. The 1.5 km exclusion zone remains in place and there is full reinjection of the increased production.
2c	Add new production evenly in the CBD and Fenton Street of 20% of the current total. This is an increase of 2000 tonnes/day. The 1.5 km exclusion zone remains in place and there is full reinjection of the increased production.
3	Increase total extraction until the model indicates a decline in temperature in the thermal outflow areas. The 1.5 km exclusion zone remains in place and there is full reinjection of the increased production.
4a	Add new production within the 1.5 km exclusion zone of 5% of the current total. This is an increase of 500 tonnes/day. The increased production shall be located evenly along Fenton Street and Sophia Street between zones of 1 and 1.5 km centred at Pohutu Geyser. There is full reinjection of the increased production.
4b	Add new production within the 1.5 km exclusion zone of 5% of the current total. This is an increase of 500 tonnes/day. The increased production shall be located evenly along Fenton Street and Sophia Street between zones of 500 m and 1.5 km centred at Pohutu Geyser. There is full reinjection of the increased production.
4c	Add new production within the 1.5 km exclusion zone of 5% of the current total. This is an increase of 500 tonnes/day. The increased production shall be located throughout the 1.5 km exclusion zone. There is full reinjection of the increased production.
4d	Add new production within the 1.5 km exclusion zone of 10% of the current total. This is an increase of 1000 tonnes/day. The increased production shall be located evenly along Fenton Street and Sophia Street between zones of 1 and 1.5 km centred at Pohutu Geyser. There is full reinjection of the increased production.
4e	Add new production within the 1.5 km exclusion zone of 10% of the current total. This is an increase of 1000 tonnes/day. The increased production shall be located evenly along Fenton Street and Sophia Street between zones of 500 m and 1.5 km centred at Pohutu Geyser. There is full reinjection of the increased production.
4f	Add new production within the 1.5 km exclusion zone of 10% of the current total. This is an increase of 1000 tonnes/day. The increased production shall be located throughout the 1.5 km exclusion zone. There is full reinjection of the increased production.
4g	Add new production within the 1.5 km exclusion zone of 20% of the current total. This is an increase of 2000 tonnes/day. The increased production shall be located evenly along Fenton Street and Sophia Street between zones of 1 and 1.5 km centred at Pohutu Geyser. There is full reinjection of the increased production.
4h	Add new production within the 1.5 km exclusion zone of 20% of the current total. This is an increase of 2000 tonnes/day. The increased production shall be located evenly along Fenton Street and Sophia Street between zones of 500 m and 1.5 km centred at Pohutu Geyser. There is full reinjection of the increased production.
4i	Add new production within the 1.5 km exclusion zone of 20% of the current total. This is an increase of 2000 tonnes/day. The increased production shall be located throughout the 1.5 km exclusion zone. There is full reinjection of the increased production.
5a	Increase the rate of heat extraction by downhole heat exchangers within the 1.5 km zone by

No.	Scenario
	50%.
5b	Increase the rate of heat extraction by downhole heat exchangers within the 1.5 km zone by 100%.
5c	Increase the rate of heat extraction by downhole heat exchangers within the 1.5 km zone by 200%.