The United Nations University

GEOTHERMAL TRAINING PROGRAMME
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IS-108 Reykjavík, Iceland

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FIVE LECTURES ON ENVIRONMENTAL EFFECTS OF GEOTHERMAL UTILIZATION

Trevor M. Hunt
Institute of Geological and Nuclear Sciences,
Taupo,
NEW ZEALAND

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PREFACE

Geothermal energy is generally regarded as benign to the environment. The exploitation of geothermal energy has, however, to be conducted in a sustainable way. New Zealand is one of the world´s pioneer countries in the development of high-temperature geothermal resources. Dr. Trevor M. Hunt, geophysicist at the Wairakei Research Centre of the Institute of Geological and Nuclear Sciences in Taupo, has been one of the key people in the exploration and the monitoring of the exploitation of the geothermal fields in New Zealand. He gave the lectures presented here as the UNU Visiting Lecturer at the UNU Geothermal Training Programme in Reykjavik in September 2000.

In his lectures, Dr. Trevor M. Hunt gives a detailed account of the environmental changes that have been caused by the operations of the geothermal power stations in Wairakei and Ohaaki in New Zealand. He demonstrates very clearly the importance of regular monitoring of geothermal fields both prior to and during exploitation and points out how the environment can best be protected and the effects of exploitation mitigated. We are very grateful to him for writing up his lecture notes and thus making the lectures available to a much larger audience than those who were so fortunate in attending his lectures in Reykjavik. The experience of Dr. Trevor M. Hunt and his colleagues in New Zealand is very valuable to the world geothermal community and will certainly help in promoting the sustainable use of geothermal resources in the world.

Since the foundation of the UNU Geothermal Training Programme in 1979, it has been customary to invite annually one internationally renowned geothermal expert to come to Iceland as the UNU Visiting Lecturer. This has been in addition to various foreign lecturers who have given lectures at the Training Programme from year to year. It is the good fortune of the UNU Geothermal Training Programme that so many distinguished geothermal specialists have found time to visit us. Following is a list of the UNU Visiting Lecturers during 1979-2000:

1979 Donald E. White	United States	1990 Andre Menjoz	France
1980 Christopher Armstead	United Kingdom	1991 Wang Ji-yang	China
1981 Derek H. Freeston	New Zealand	1992 Patrick Muffler	United States
1982 Stanley H. Ward	United States	1993 Zosimo F. Sarmiento	Philippines
1983 Patrick Browne	New Zealand	1994 Ladislaus Rybach	Switzerland
1984 Enrico Barbier	Italy	1995 Gudm. Bödvarsson	United States
1985 Bernardo Tolentino	Philippines	1996 John Lund	United States
1986 C. Russel James	New Zealand	1997 Toshihiro Uchida	Japan
1987 Robert Harrison	UK	1998 Agnes G. Reyes	Philippines/N.Z.
1988 Robert O. Fournier	United States	1999 Philip M. Wright	United States
1989 Peter Ottlik	Hungary	2000 Trevor M. Hunt	New Zealand

With warmest wishes from Iceland,

Ingvar B. Fridleifsson, director,
United Nations University
Geothermal Training Programme

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LECTURE 1

GEOTHERMAL AND THE ENVIRONMENT

1. INTRODUCTION

For tens of thousands of years mankind has functioned as an integral part of the environment, and until recently has had no greater impact than any other animal species. However, as our technological skills have increased, especially in the last century, so has our capacity to cause environmental changes. Such changes, in themselves, are not necessarily a problem, but it is the fact that so many of the changes have been unpredictable and irreversible in the short term that has caused problems. This is in part due to our poor understanding of the environment and of environmental processes at a time when our ability to alter the environment has never been greater. For example, let us consider what is possibly the greatest environmental problem at present – that of global warming. Scientific measurements show that there has been a 12% increase in the carbon dioxide content of the atmosphere since 1880, and this has been linked to various meteorological changes which have occurred in the latter part of the 20 th century. However, there is still a great deal of scientific debate about the processes involved. Current thinking favours the theory that much of this increase in carbon dioxide is associated with increased energy use, and in particular with the burning of fossil fuels combined with reduction of forest areas that are carbon "sinks".

Geothermal energy is generally accepted as being an environmentally benign energy source, particularly when compared to fossil fuel energy sources. Geothermal developments in the last 40 years, however, have shown that it is not completely free of adverse impacts on the environment. These impacts are becoming of increasing concern, and to an extent which may now be limiting developments. History shows that hiding or ignoring such problems can be counterproductive to development of an industry because it may lead to a loss of confidence in that industry by the public, regulatory, and financial sectors. A good example of the consequences of ignoring problems is the nuclear power industry. If our aim is to further the use of geothermal energy, then all possible environmental effects should be clearly identified, and countermeasures devised and adopted to avoid or minimise their impact.

1.1 What is the "Environment" ?

Firstly it may be worthwhile to consider what is the "environment," and why it should be preserved or protected. Some dictionary definitions are:

1. The Oxford dictionary (Brown, 1993) defines environment as *"the set of circumstances or conditions … in which a person or community lives, works, develops, etc, or a thing exists or operates; the external conditions affecting the life of a plant or animal"*.

2. The Encyclopaedia of environmental science (Parker, 1980) considers it is *"the sum of all external conditions and influences affecting the life and development of organisms"*.

3. The Merriam Webster Collegiate dictionary (Internet) defines it as:
   a: *"The complex of physical, chemical, and biotic factors (as climate, soil, and living things) that act upon an organism or an ecological community and ultimately determine its form and survival."*
   b: *"The aggregate of social and cultural conditions that influence the life of an individual or community."*

The term environment is therefore generally used in a broad sense to encompass not only the physical conditions, but also the cultural and spiritual conditions of people living nearby.

1.2 What is the geothermal environment?

Natural thermal features

A major component of the geothermal environment is the beautiful natural thermal features which vary in colour and form. Their environmental importance is increased because they are rare on a world-wide basis, and often fragile. The main types of natural features are:

- Geyser – hot spring which periodically erupts a jet of hot water and steam;
- Fumarole – vent from which steam is emitted at high velocity;
- Hot spring and pool – a vent from which hot water flows, or depression into which hot water collects; often ebullient. Edges may be raised by precipitation of silica or calcium carbonate;
- Silica sinter terrace – terrace formed of opaline silica precipitated from waters of geysers and hot springs. Where the waters originate in calcareous rocks (limestones) the mineral precipitated will be travertine (calcium carbonate). Travertine terraces are rare, but splendid examples are found in Yellowstone National Park (USA) and at Pamukkale (Turkey);
- Thermal area – area of heated ground. It is often bare, or has only stunted, heat-tolerant vegetation;
- Mud pool – hot pool in which adjacent rock or soil has been dissolved to form a viscous mud, usually sulfurous and often multi-coloured;
- Algal mat – mat of coloured algae found in hot flowing streams carrying water away from geysers or hot pools. Colours range from white (hottest water) through orange and green to black (coolest water);
- Thermophyllic plant – plant which tolerates or thrives in hot ground. These may be found elsewhere but only in much warmer climates.

Cultural significance

- Myths and legends – thermal features are often associated with myths and legends in native peoples culture. For example, the native Maori people of New Zealand have a legend that the thermal areas of NZ were formed when fire gods, summoned from far away and travelling underground, surfaced looking for the person who called them;
- Spiritual – many societies which use geothermal energy incorporate it into their ceremonies. For example, in Beppu (Japan) they hold a Hot Spring Festival every year.

Cultural uses

- Bathing in hot pools – bathing in hot pools is common in most countries where geothermal waters are available. Bathing in geothermal waters is often claimed to have special medicinal properties, and in New Zealand geothermal waters are used in the government hospital at Rotorua for the treatment of arthritis and skin diseases;
- Washing – clothes are washed in warm streams;
- Cooking – boiling hot pools are used for cooking. Food is placed in a woven basket and lowered into the hot pool. This is still done in Japan and New Zealand, but mainly for tourists;
- Minerals – in primitive native societies, ochre formed from hydrothermal alteration of rocks was used to paint the face and body. At present time, sulfur and zeolite minerals are collected from fumarolic areas.

Economic uses

- Tourism – because of their relative rarity, many thermal areas containing beautiful natural thermal features are tourist destinations;
- Low impact use – in many places where there is warm or hot geothermal water it is used for low-impact agricultural or industrial purposes; for example: fruit and crop drying, heating greenhouses, and fish farming. Small communities often develop around these places.

1.3 Why preserve the environment?

The most compelling reasons why we should try and preserve the environment are:

Self respect
Most human cultures value their surroundings, even to the extent of significantly modifying them to enhance their beauty or desirability. It is generally recognised that the destruction of beautiful natural thermal features such as geysers, hot springs and silica terraces is unacceptable. The famous American philosopher Thoreaux (1860) said: *"What is the use of a house if you have not got a tolerable planet to put it on?"*

Self-preservation
Few advanced living organisms will significantly alter or destroy their surroundings because this is likely to threaten their continued existence as a species.

Maintaining our heritage
The natural environment is a heritage, passed to us by preceding generations, and it is our responsibility to pass it undamaged to future generations.

Economic
Changing the environment can have negative economic effects. In the case of geothermal development, the destruction, loss or modification of beautiful natural thermal features can badly affect tourism which is often a major source of revenue and employment. For example, in New Zealand, international tourism is the third largest source of overseas income, and the natural thermal features are prime tourist destinations. For this reason many geothermal areas with thermal features which have tourist potential have been designated as scenic reserves by the New Zealand government and no geothermal developments are allowed in them.

To meet national and international obligations
In most countries, industrial development (including geothermal) is contingent on the developer obtaining a permit (from a regulatory authority) which involves assessing the impact the development may have on the environment. In many countries the permitting process involves public submissions and hearings, and permits are extremely difficult to obtain if significant environmental effects are predicted.

Preservation of the environment is not merely a local issue but an international concern: Of 27 Principles proclaimed by the 1992 United Nations Conference on Environment and Development (Earth Summit), 21 refer specifically to the environment. This conference was held, at Rio de Janeiro, Brazil (June 3-14, 1992), to reconcile world-wide economic development with protection of the environment. It was the largest gathering of world leaders in history, with 117 heads of state and representatives of 178 nations attending. Through treaties and other documents signed at the conference, most of the world's nations nominally committed themselves to the pursuit of economic development in ways that would protect the Earth's environment and its non-renewable resources.

The main documents agreed upon at the Earth Summit were:

The Convention on Biological Diversity
This is a binding treaty requiring nations to take inventories of their plants and wild animals and protect their endangered species.

The Framework Convention on Climate Change, (Global Warming Convention)
This is a binding treaty that requires nations to reduce their emission of carbon dioxide, methane, and other "greenhouse" gases thought to be responsible for global warming. However, the treaty stopped short of setting binding targets for emission reductions.

The Declaration on Environment and Development, (Rio Declaration)
This laid down 27 broad, non-binding principles for environmentally sound development.

Agenda 21
This outlined global strategies for cleaning up the environment and encouraging environmentally sound development.

The Statement of Principles on Forests
This non-binding statement aimed at preserving the world's rapidly vanishing tropical rainforests, and

recommended that nations monitor and assess the impact of development on their forest resources and take steps to limit the damage done to them.

The Earth Summit was hampered by disputes between the wealthy industrialised nations of the North (*i.e.,* western Europe and North America) and the poorer countries of the South (*i.e.,* Africa, Latin America, the Middle East, and parts of Asia). In general, the countries of the South were reluctant to hamper their economic growth with the environmental restrictions urged upon them by the North unless they received increased financial aid, which they claimed would help make environmentally sound growth possible.

2. BENEFITS OF GEOTHERMAL DEVELOPMENT

2.1 Energy savings

According to Lund (2000) the total geothermal electricity produced in the world is equivalent to saving 12.5 Mt (million tonnes) of fuel oil per year (assuming 0.35 efficiency factor). The total direct-use and geothermal heat pump energy use in the world is equivalent to savings of 13.1 Mt of fuel oil per year (0.35 efficiency factor). If the replacement energy for direct-use was provided by burning the fuel directly, then about half this amount would be saved in heating systems (35% vs. 70% efficiency). If the savings in the cooling mode of geothermal heat pumps is considered, then this is equivalent to additional savings of 1.2 Mt/yr of fuel oil (Table 1).

TABLE 1: Fuel oil and carbon savings (annual) from geothermal energy production; taken from Lund (2000)

Fuel oil (10^6)		**Carbon (10^6 t)**		
Barrels	**Tonnes**	**Natural gas**	**Oil**	**Coal**
179.1	26.7	5.56	23.80	27.64

2.2 Reduced greenhouse gas emissions

Electricity generation from geothermal resources involves much lower greenhouse gas (GHG) emission rates than that from fossil fuels. According to the International Atomic Energy Agency (IAEA), replacing one kilowatt-hour (kWh) of fossil power with a kilowatt-hour of geothermal power reduces the estimated global warming impact by approximately 95%. This estimate includes emissions from the "full energy chain," which includes all of the upstream and downstream processes necessary for power generation. At first reading this may seem an exaggeration but the extraction, refinement, and transport of fossil fuels can entail substantial greenhouse gas emissions. For example, methane, the main component of natural gas, is a potent greenhouse gas, so leakage from systems (pipelines, tankers) which transport natural gas may considerably increase the global warming impact of natural gas-fired power generation.

Most geothermal power plants release a small amount of carbon dioxide (CO_2), which is contained in the fluid. The full-energy-chain emissions from geothermal power generation had been estimated in three studies reviewed by the IAEA. A 1989 study estimated emissions equivalent to 57 grams of carbon dioxide per kWh of net electricity generation, while two 1992 studies estimated 40 and 42 grams per kWh. For power generation from fossil fuels, the IAEA estimated greenhouse gas emissions equivalent to 460-1290 grams of CO_2 per kWh (Fig. 1). However, the literature on full-energy-chain GHG emission rates is scant and imperfect, so the values developed by the IAEA and shown in Figure1 should not to be considered definitive.

According to Lund (2000), the equivalent savings in the production of CO_2 from geothermal electricity production from fuel oil is 40.2 Mt and from direct-use 42.0 Mt. The corresponding figures for natural gas and coal are 9.5 and 46.9 Mt for electricity, and 9.9 and 49.0 for direct-use (at 35% plant efficiency). Similar numbers for natural gas, oil and coal can be determined for sulfur oxides (SO_x) and nitrogen oxides (NO_x) at 0, 0.25 and 0.26 Mt and 2.2, 7.6 and 7.6 kt (thousand tonnes) respectively for electricity, and 0, 0.26 and 0.28 Mt and 2.3, 7.9 and 7.9 kt respectively for direct-use. For direct-use, the values would be approximately half if the heat energy was used directly.

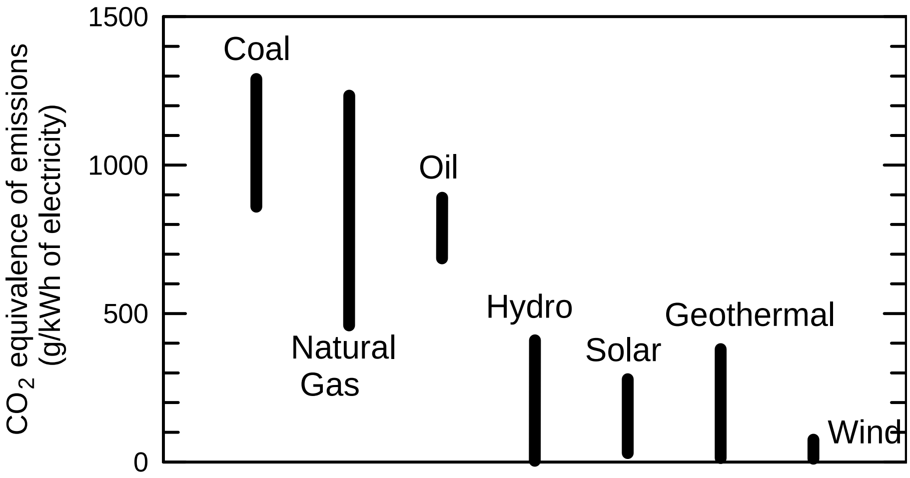

FIGURE 1: Relative amounts of greenhouse gas emissions from various types of electricity generation methods, data expressed as CO_2 equivalents; taken from Geothermal Energy News (May 1998), and geothermal data adjusted on basis of data from ETSU (1998)

In total, the savings from present worldwide geothermal energy production, both electric and direct-use, are summarised in Tables 1 and 2.

TABLE 2: CO_2, SO_x and NO_x savings (annual) from geothermal energy production; taken from Lund (2000)

CO_2 (10^6 t)			**SO_x (10^6 t)**			**NO_x (10^6 t)**		
Natural gas	Oil	Coal	Natural gas	Oil	Coal	Natural gas	Oil	Coal
19.4	82.2	95.9	0	0.51	0.54	4.5	15.5	15.5

2.3 Reduced sulphur gas emissions

The amount of sulphur gases (mainly H_2S) emitted from a geothermal power station (average 0.03 g/kWh) is less than 2% of that emitted from equivalent size coal- and oil-fired power stations (9.23 and 4.95 g/kWh, respectively).

3. ENVIRONMENTAL IMPACTS

Geothermal energy does have some environmental impacts, most of which are associated with the exploitation of high-temperature geothermal systems. In Table 3 the possibilities of environmental effects of geothermal development both for low-temperature areas and high-temperature areas are summarised.

3.1 Drilling operations

Exploitation of both low-temperature and high-temperature systems involves drilling wells to depths of 500-2500 m; this requires large drilling rigs and may take several weeks or months. For high-temperature systems the location of the drilling site is important, although directional drilling techniques have reduced this in recent times. The main environmental effects of drilling are shown here below.

TABLE 3: Possibilities of environmental effects of geothermal development

	Low-temperature systems	**High-temperature systems**	
		Vapour-dominated	**Liquid-dominated**
Drilling operations:			
Destruction of forests and erosion	●	● ●	● ●
Noise	● ●	● ●	● ●
Bright Lights	●	●	●
Contamination of ground-water by drilling fluid	●	● ●	● ●
Mass withdrawal:			
Degradation of thermal features	●	● ●	● ● ●
Ground subsidence	●	● ●	● ● ●
Depletion of groundwater	○	●	● ●
Hydrothermal eruptions	○	●	● ●
Ground temperature changes	○	●	● ●
Waste liquid disposal:			
Effects on living organisms			
surface disposal	●	●	● ● ●
reinjection	○	○	○
Effects on waterways			
surface disposal	●	●	● ●
reinjection	○	○	○
Contamination of groundwater	●	●	●
Induced seismicity	○	● ●	● ●
Waste gas disposal:			
Effects on living organisms	○	●	● ●
Microclimatic effects	○	●	●

○ No effect ● ● Moderate effect
● Little effect ● ● ● High effect

Impact of access and field development
The construction of road access to drilling sites can involve destruction of forests and vegetation which, particularly in tropical areas with high rainfall (Indonesia, Philippines), can result in erosion. Such erosion can result in large amounts of silt being carried by the streams and rivers draining the development area, This silt can affect fish in the river and may even affect fish in coastal waters near the mouth of the river. The silt may also deposit on the river bed where the gradient (flow rate) is less, causing the bed of the river to be raised and make the adjacent land more likely to be flooded during periods of high rainfall.

Effects of drilling operations
Drilling creates noise, fumes and dust which can disturb animals and humans living nearby. Typical noise levels (in approximate order of intensity) are:

- Air drilling – 120 dBa (85 dBa with suitable muffling);
- Discharging wells after drilling (to remove drilling debris) – up to 120 dBa;
- Well testing – 70-110 dBa (if silencers used);
- Heavy machinery (earth moving during construction) – up to 90 dBa;
- Well bleeding – 85 dBa (65 dBa if a rock muffler is used);
- Mud drilling – 80 dBa;

- Diesel engines (to operate compressors and provide electricity) – 45-55 dBa if suitable muffling is used.

The characteristics of the site (e.g. its topography) and meteorological conditions will also have an influence. To put the above noise levels into context, 120 dBa is the pain threshold (at 2-4000 Hz), noise levels in a noisy urban environment are 80-90 dBa, in a quiet suburban residence about 50 dBa and in a wilderness area 20-30 dBa (DiPippo, 1991; Armannsson and Kristmannsdottir, 1993). Noise is attenuated by distance travelled in air; there is approximately 6 dB attenuation every time the distance is doubled, but lower frequencies are attenuated less than higher frequencies. Thus, low rumbling noises from drill rigs and silencers carry much further than high frequency steam discharge noises.

Continuous drilling involves the use of powerful lamps to light the work site at night which can disturb local residents, domestic and wild animals.

Disposal of waste drilling fluid
In the past it was common practice to discharge waste fluids into nearby waterways.

3.2 Mass withdrawal

Large-scale exploitation of liquid-dominated high-temperature geothermal systems involves the withdrawal of large volumes of geothermal fluid. For example, between 1958 and 1991 more than 1700 Mt of fluid were withdrawn from the Wairakei geothermal field (New Zealand); assuming an average temperature of 200°C this represents nearly 2 km^3 of fluid (Hunt, 1995). In geothermal power schemes where the fluid withdrawn is reinjected, the reinjection wells are generally located away from the production wells to reduce the chances of the cooler reinjected water returning to the production wells and reducing the temperature of production fluids. Even if all the waste liquid is reinjected, there may be a large mass loss (up to 30% of that withdrawn) associated with discharge of water vapour into the atmosphere from the power station. A major consequence of the mass loss from parts of the field is the formation of a 2-phase (steam + water) zone in the upper part of the reservoir, and as production continues this zone increases in size and the pressures (both in and below this zone) decrease. At Wairakei, the deep (liquid phase) pressures declined by about 0.5 MPa (5 bar) during exploratory drilling, and a further 1.7 MPa (17 bar) during the first ten years of production, although subsequent pressure declines have been less than 0.5 MPa (Figure 2). Pressure declines in the reservoir, as a result of mass withdrawal and net mass loss, are an important cause of environmental changes at or near the surface.

Degradation of thermal features
In their natural, unexploited state many high-temperature geothermal systems are manifested at the surface by thermal features such as geysers, fumaroles, hot springs, hot pools, mud pools, sinter terraces and thermal ground with special plant species. Often these features are of great cultural significance, as well as being important tourist attractions. The thermal features result from the (upward) leakage of

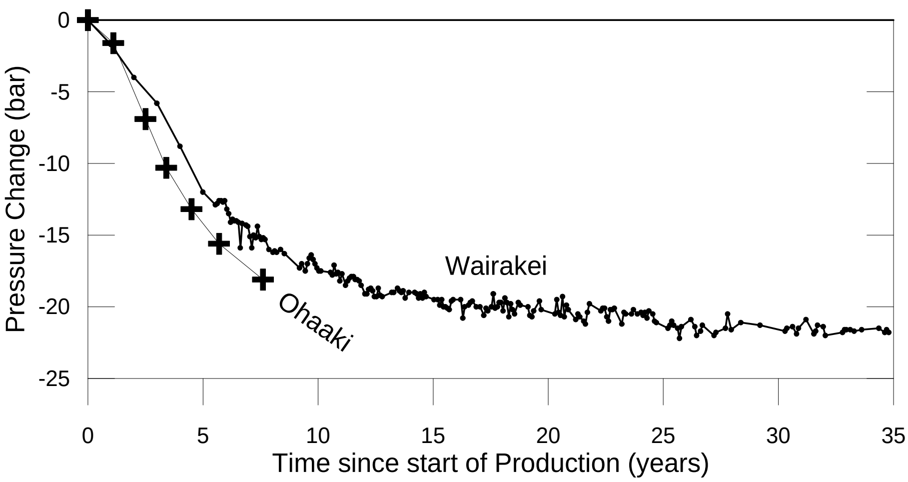

FIGURE 2: Deep reservoir pressure changes since start of production at the liquid-dominated, high-temperature geothermal fields of Wairakei (1958) and Ohaaki (1988), in New Zealand; note the rapid decline in pressure during the first 10 years of production

boiling geothermal fluid from the upper part of the reservoir, through overlying cold groundwater, to the surface.

Historical evidence shows that natural thermal features have been affected, often severely, during the development and initial production stages of most high-temperature geothermal systems. At Wairakei (New Zealand), nearly all the thermal features in the Waiora and Geyser Valleys (including more than 20 geysers) have died. At Ohaaki (New Zealand), the level and temperature of water in the Ohaaki Pool have declined since exploration drilling and reservoir testing began. Such effects are not confined to liquid-dominated systems. At Larderello (Italy) where the original natural activity consisted of numerous steam and gas jets, activity has now largely ceased, and at The Geysers (USA) there has been a decrease in the flow from hot springs since exploitation began.

Scientific evidence shows that the decline in thermal features is associated with the decline in reservoir pressure. As the pressure declines, so also does the amount of geothermal fluid reaching the surface and hence the thermal features decline in size and vigour. If pressures fall further then the features may die and the flow may reverse with cold groundwater flowing down into the reservoir; once this situation has occurred there may be little hope of resurrecting the features, at least within a human lifetime.

Depletion of groundwater
Most high-temperature geothermal systems are overlain by a cold groundwater zone. If exploitation of the system results in a large pressure drop in the reservoir, this groundwater may be drawn down into the upper part of the reservoir in places where there are suitable high-permeability paths (such as faults); such a situation is called a *cold downflow* (Bixley, 1990). If the lateral permeability of the rocks in the groundwater zone is low then a downflow may result in a drop in the groundwater level. For example, at Wairakei, a localised drop of more than 30 m in groundwater level has occurred associated with a cold downflow.

Downflows, and groundwater level changes, may also occur as a result of breaks in the casing of disused wells (Bixley & Hattersley, 1983).

Ground deformation
Withdrawal of fluid from an underground reservoir can result in a reduction of formation pore pressure which may lead to compaction in rock formations having high compressibility and result in subsidence at the surface. Subsidence has also been observed in groundwater and petroleum reservoirs. Horizontal movements also occur. Such ground movements can have serious consequences for the stability of pipelines, drains and well casings in a geothermal field. If the field is close to a populated area, then subsidence could lead to instability in dwellings and other buildings; in other areas, the local surface watershed systems may be affected.

The largest recorded subsidence in a geothermal field (15 m) is in part of the Wairakei field (New Zealand) This subsidence has caused:

- Compressional and tensional strain on pipelines and lined canals;
- Deformation of drill casing;
- Tilting of buildings and the equipment inside;
- Breaking of road surfaces;
- Alteration of the gradient of streams and rivers.

Ground movements have been recorded in other high-temperature geothermal fields in New Zealand, at Cerro Prieto (Mexico), Larderello (Italy), and The Geysers (USA). Subsidence in liquid-dominated fields has been greater than in vapour-dominated fields, because the former are often located in young, relatively-poorly compacted volcanic rocks and the latter are generally in older rocks having lower porosity.

Ground temperature changes
The formation and expansion of a 2-phase zone in the early stages of exploitation of a liquid-dominated geothermal system can also alter the heat flow. Steam is much more mobile than water; it can move through small fractures that are impervious to water and can move much more quickly through larger fractures. The generation and movement of steam can therefore result in increased heat flow and increased ground temperatures so that vegetation becomes stressed or killed.

At Wairakei, heat flow from natural thermal features was about 400 MW prior to the start of exploitation in 1958, increased to a peak of nearly 800 MW by the mid 1960s, and has since declined to about 600 MW (Allis, 1981). Most of this increase was associated with increased thermal activity in the Karapiti thermal area, which is situated 3 km south-west of the main production borefield. These changes have been attributed to steam rising to the surface through fissures that were previously impervious to water.

3.3 Waste liquid disposal

Most geothermal energy developments bring fluids to the surface in order to mine heat contained within them. In high-temperature liquid-dominated geothermal fields the volumes of resultant liquid waste involved may be large: at Wairakei, a medium-sized power station (156 MW), it is currently about 5800 m^3/hr. For vapour-dominated systems it is less, and for low-temperature systems it is very much less: at Chevilly-Larue (France) it is only about 3 m^3/hr. The waste fluid is disposed of by putting it into waterways or evaporation ponds, or reinjecting it deep into the ground. Surface disposal causes more environmental problems than reinjection.

Environmental problems are due not only to the volumes involved, but also to the relatively high temperatures and toxicity of the waste fluid. For example, at Wairakei the waste water has a temperature of about 140°C. The chemistry of the fluid discharge is largely dependent on the geochemistry of the reservoir, and the operating conditions used for power generation and will be different for different fields (Webster, 1995). For example, fluids from the Salton Sea field (USA), which is hosted by evaporite deposits, are acidic and highly saline (pH <5, [Cl] = 155 000 ppm). At the other extreme, those of the Hveragerdi field (Iceland) are alkaline and of very low salinity (pH >9, [Cl] <200 ppm). Most high-temperature geothermal bore waters include high concentrations of at least one of the following toxic chemicals: lithium (Li), boron (B), arsenic (As), hydrogen sulfide (H_2S), mercury (Hg), and sometimes ammonia (NH_3). Fluids from low-temperature reservoirs generally have a much lower concentrations of contaminants.

Most of the chemicals are present as solute and remain in solution from the point of discharge, but some are taken up in river or lake bottom sediments, where they may accumulate to high concentrations. The concentrations in such sediments can become greater than the soluble concentration of the species in the water, so that re-mobilisation of the species in the sediment, such as during an earthquake or flood, could result in a potentially toxic flush of the species into the environment. Chemicals which remain in solution may be taken up by aquatic vegetation and fish (Webster & Timperly, 1995), and some can also move further up the food chain into birds and animals residing near the river. For example, in New Zealand, annual geothermal discharges into the Waikato River contain 50 kg mercury, and this is regarded as partly responsible for the high concentrations of mercury (often greater than 0.5 mg/kg of wet flesh) in trout from the river and high (greater than 200 μg/kg) sediment mercury levels.

Effects on living organisms
If hot waste water from a standard steam-cycle power station is released directly into an existing natural waterway, the increase in temperature may kill fish and plants near the outlet. Release of untreated waste into a waterway can result in chemical poisoning of fish, and also birds and animals which reside near the water because some of the toxic substances move up the "food chain".

Effects on waterways
Release of large volumes of waste water into a waterway may increase erosion, and if uncooled and untreated there may be precipitation of minerals such as silica near the outlet surface disposal

Contamination of groundwater
Release of waste water into cooling ponds or waterways may result in shallow groundwater supplies becoming contaminated and unfit for human use

Induced seismicity
Most high-temperature geothermal systems lie in tectonically active regions where there are high levels of stress in the upper parts of the crust; this stress is manifested by active faulting and numerous earthquakes. Studies in many high-temperature geothermal fields have shown that exploitation can result in an increase (above the normal background) in the number of small magnitude earthquakes (microearthquakes) within the field. It is believed the increase is caused by reinjection because when reinjection is stopped the number of small earthquakes decreases, and when it is restarted the number increases (Sherburn et al., 1990). High wellhead reinjection pressures increase the pore pressure at depth particularly in existing fractures, which allows movement to suddenly release the stress and resulting in an earthquake. This phenomenon occurs in both liquid- and vapour-dominated fields, but has not been observed in low-temperature fields. Detailed studies show that the induced microearthquakes cluster (in space) around and below the bottom of reinjection wells and so the effects at the surface are generally confined to the field (Stark, 1990). To date no serious damage has been caused by such earthquakes, but they do frighten people.

3.4 Waste gas disposal

Gas discharges from low-temperature systems do not usually cause significant environmental impacts. In high-temperature geothermal fields, power generation using a standard steam-cycle plant may result in the release of non-condensable gases (NCG) and fine solid particles (particulates) into the atmosphere (Webster, 1995). In vapour-dominated fields in which all waste fluids are reinjected, non-condensable gases in steam will be the most important discharges from an environmental perspective.

The emissions are mainly from the gas exhausters of the power station, often discharged through a cooling tower. Gas and particulate discharges during well drilling, bleeding, cleanouts and testing, and from line valves and waste bore water degassing, are usually insignificant. The concentration of NCG varies not only between fields but can also from well to well within a field, thus changes to the proportion of steam from different wells may cause changes in the amounts of NCG discharged.

Gas concentrations and compositions cover a wide range, but the predominant gases are carbon dioxide (CO_2) and hydrogen sulphide (H_2S).

Carbon dioxide
Carbon dioxide occurs in all geothermal fluids but is most prevalent in fields in which the reservoir contains sedimentary rocks, and particularly those with limestones. Carbon dioxide is generally the most abundant NCG. It is colourless and odourless, and is heavier than air and can thus accumulate in topographic depressions where there is still air. It is not highly toxic (c.f. hydrogen sulfide) but at high concentrations it can be fatal due to alteration of pH in the blood. A 5% concentration in air can result in shortness of breath, dizziness, and mental confusion. At 10% a person will normally lose consciousness and quickly be asphyxiated. Exposure standards range from 5000 to 30,000 ppm (for 10 min.). There is some evidence that in high-temperature fields the amount of CO_2 discharged (per unit mass withdrawn) decreases with time as a result of de-gassing of the deep reservoir fluid and a decline in heat transfer from the formations occurs.

Hydrogen sulphide
H_2S is characterised by a "rotten egg odour" detectable by humans at very low concentrations of about 0.3 ppm. At such concentrations it is primarily a nuisance, but as the concentration increases, it may irritate and injure the eye (10 ppm), the membranes of the upper respiratory tracts (50-100 ppm), and lead to loss of smell (150 ppm). At a concentration of about 700 ppm it is fatal. Because H_2S is heavier than air it can accumulate in topographic depressions where there is still air, such as well cellars and the basements of buildings near the gas exhausters. The disappearance of the characteristic smell at concentrations greater than 150 ppm is especially dangerous because it leads to people failing to recognise potentially fatal concentrations. Exposure standards range from 10 to 50 ppm (10 min.). In sparsely populated areas, H_2S emissions may not prove a problem, and at many sites, there are already natural emissions from fumaroles, hot springs, mudpots etc. H_2S emissions can vary significantly from field to field, depending on the amount of H_2S in the geothermal fluid, and the type of plant used to exploit the reservoir (Table 4).

H_2S dissolved in water aerosols, such as fog, reacts with atmospheric oxygen to form more oxidised sulphur-bearing compounds; some of these compounds have been identified as components of "acid rain", but a direct link between H_2S emission and acid rain has not been established. U.S. Occupational Safety & Health ceiling level for H_2S is 14 mg/m^3, but an ambient air quality standard of 0.042 mg/m^3 is used in California.

TABLE 4: H_2S emissions from some geothermal plants; taken from ETSU (1998)

Field	H_2S emission (g/kWh)	Reference
Wairakei, NZ	0.5	Barbier, 1991
The Geysers, USA	1.9	Barbier, 1991
Lardarello, Italy	3.5	Barbier, 1991
Cerro Prieto, Mexico	4.2	Barbier, 1991
Krafla, Iceland	6.0	Armannsson and Kristmannsdottir, 1992
Ohaaki, NZ	6.4	Barbier, 1991

Other gases
Geothermal power stations do not emit oxides of nitrogen (NO_x), which combine photochemically with hydrocarbon vapours to form ground-level ozone which harms crops, animals and humans. However, geothermal gases may contain ammonia (NH_3), trace amounts of mercury (Hg) and boron (B) vapour, and hydrocarbons such as methane (CH_4). Ammonia can cause irritation of the eyes, nasal passages and respiratory tract, at concentrations of 5 to 32 ppm. Inhalation or ingestion of mercury can cause neurological disorders. Boron is an irritant to the skin and mucus membranes, and is also phytotoxic at relatively low concentrations. but these metals are generally emitted in such low quantities that they do not pose a human health hazard. The metals may also be deposited on soils and, if leached from there, they may contribute to groundwater contamination.

Binary plants use low-boiling point fluid, commonly iso-pentane, which may escape from the plant over a period of time. The gas phase may be recognised in the steam, and values of up to 4000 ppm have been recorded.

Effects on living organisms
The impacts of H_2S discharge will depend on local topography, wind patterns and land use. The gas can be highly toxic, causing eye irritation and respiratory damage in humans and animals, and has an unpleasant odour. Boron, NH_3, and (to a lesser extent) Hg, are leached from the atmosphere by rain, leading to soil and/or vegetation contamination (Webster, 1995). Boron, in particular, can have a serious impact on vegetation. Contaminants leached from the atmosphere can also affect surface waters and affect

aquatic life. Details of biological impacts of these gases are given by Webster & Timperley (1995).

Microclimatic effects
Even in geothermal power schemes which have complete reinjection, a considerable amount of gas (mainly steam) may be lost to the atmosphere. For example, at Ohaaki, of 70 Mt of fluid withdrawn (1988 - 1993) about 20 Mt (nearly 30%) was discharged to the atmosphere. Such discharges of warm water vapour may have a significant effect on the climate in the vicinity of the power station, depending on the topography, rainfall, and wind patterns. Under certain conditions there may be increased fog, cloud or rainfall. Microclimatic effects are mainly confined to large power schemes on high-temperature fields; exploitation of low-temperature geothermal systems does not cause significant microclimatic effects.

3.5 Landscape impacts

Land use
Power plants must be built on the site of geothermal reservoirs because long fluid transmission lines are expensive, and they result in losses of pressure and temperature. At the site, land is required for well pads, fluid pipelines, power station, cooling towers and electrical switchyard. The actual area of land covered by the total development can be significantly higher than the area required for these components. For example at Cerro Prieto field (Mexico) the area covered by the well pads (12 ha) is only 2% of the total area (540 ha) encompassing all the wells and the 180 MWe power station.

In many cases, the land between the well pads and pipes may continue to be used for other purposes, although at some sites the nature of the development may make this impracticable. For example, at Wairakei, where the development is located in a relatively narrow valley, there are a lot of individual pipelines, separation plants, steam discharges and surface hot water drains which effectively divide the land up into very small parcels. This precludes the land being used for anything else, although it is unlikely the land would have had another productive use. In contrast, the development at nearby Ohaaki (Broadlands) field, the design of the development has resulted in much larger parcels of land between the pipelines and the road system so the land will continue to be used. Areas previously used for stock and arable farming are now used mainly for sheep farming, and land which was mainly self sown pine scrub is worked as a productive forest.

The impact on land use depends on the type of development, and the original use of the land.

Visual intrusion
A geothermal plant must be located close to the resource, so there is often little flexibility in the siting of the plant. Geothermal plants generally have a low profile, and need not have a tall stack like coal and oil fired power plants. However, their visual impact may still be significant, as geothermal fields are often situated in areas of outstanding natural beauty. Any associated natural thermal features (e.g. geysers and hot pools) may be a tourist attraction or of historical and cultural significance. Visual impact may be particularly high during drilling due to the presence of tall drill rigs.

3.6 Catastrophic events

Like any large engineering development, catastrophic events may occur during the construction and operation of a large-scale geothermal power scheme.

Landslides
For schemes in areas of high relief and steep terrain, landslides are a potential hazard. Landslides may be triggered either:

a) Naturally, by heavy rain or earthquake; or
b) As a result of construction work, which may have removed the “toe” of the slide.

Such events are relatively rare but the result may be severe, such as for the landslide on 5 January 1991 in Zunil field (Guatemala), when 23 people were killed (Goff & Goff, 1997).

Hydrothermal eruptions

Although rare, hydrothermal eruptions (also called “hydrothermal” or “phreatic explosions”) constitute a potential environmental hazard in high-temperature liquid-dominated geothermal fields (Bixley and Browne, 1988; Bromley & Mongillo, 1994). Eruptions occur when the steam pressure in near-surface aquifers exceeds the overlying lithostatic pressure and the overburden is then ejected, generally forming a crater 5-500 m in diameter and up to 500 m in depth (although most are less than 10 m deep).

A hydrothermal eruption occurred on 13 October 1990 in the Agua Shuca fumarole area of Ahuachapan field (El Salvador) which killed or injured people living nearby (Goff & Goff, 1997). At Wairakei field, hydrothermal eruptions began (or significantly increased) in the Karapiti thermal area after development of the field began. At least 15 eruptions have occurred here but fortunately nobody has been killed or injured.

4. SUMMARY

- Use of geothermal energy has low environmental impact, particularly when compared with fossil fuels.
- Most environmental impacts are associated with the exploitation of high-temperature systems, particularly in liquid-dominated fields (Table 3).
- Exploitation of low-temperature systems rarely has any significant environmental effects.

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LECTURE 2

EXAMPLES OF ENVIRONMENTAL CHANGES

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

1. CHANGES AT WAIRAKEI GEOTHERMAL FIELD (NEW ZEALAND)

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

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

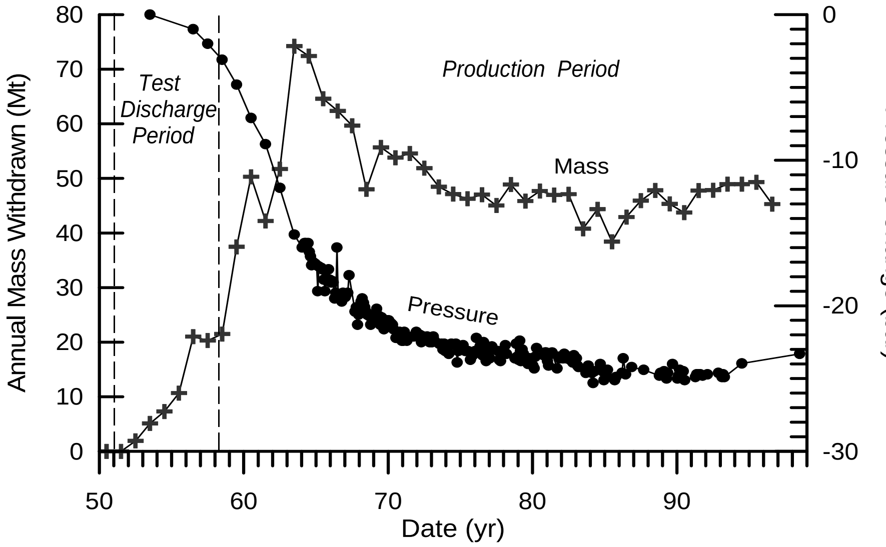


FIGURE 3: Mass withdrawal and pressure changes at Wairakei field, pressure is on average at -152 m a.s.l.; taken from Hunt & Glover (1996) and updated

Until the late 1990's, all the fluid withdrawn was discharged into the nearby Waikato River (99.95%) or into the atmosphere (0.05%), except for about 5 Mt reinjected during tests. Fluid withdrawn is 2-phase; on average about 80% (by weight) at the wellhead is liquid.

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

1.1 Pressure changes

Withdrawal during the test discharge period resulted in deep-liquid pressures decreasing by about 3 bar

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

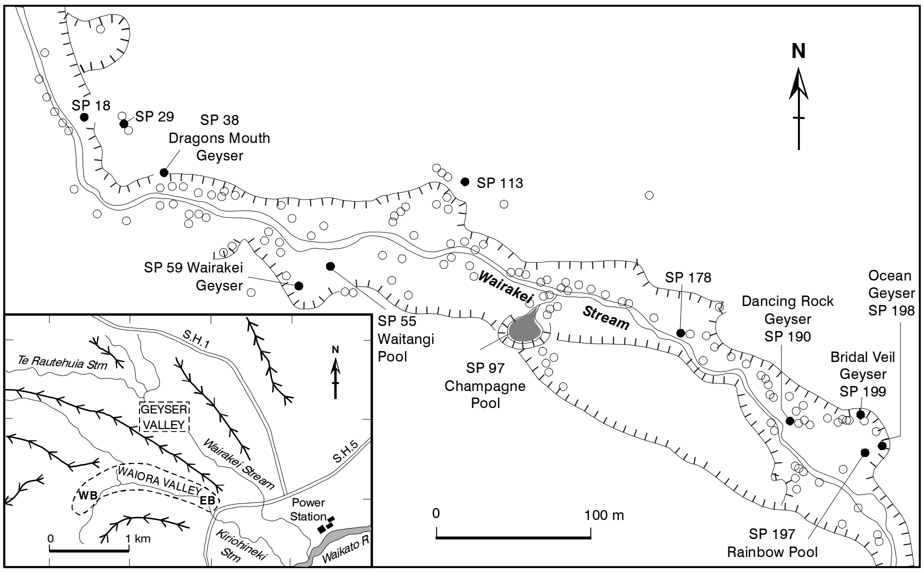


FIGURE 4: Location of thermal features in Geyser Valley, Wairakei; inset map shows the location of Geyser Valley relative to Eastern (EB) and Western (WB) borefields

1.2 Changes to natural thermal features

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

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

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

Decrease in flow rate from hot springs and pools

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

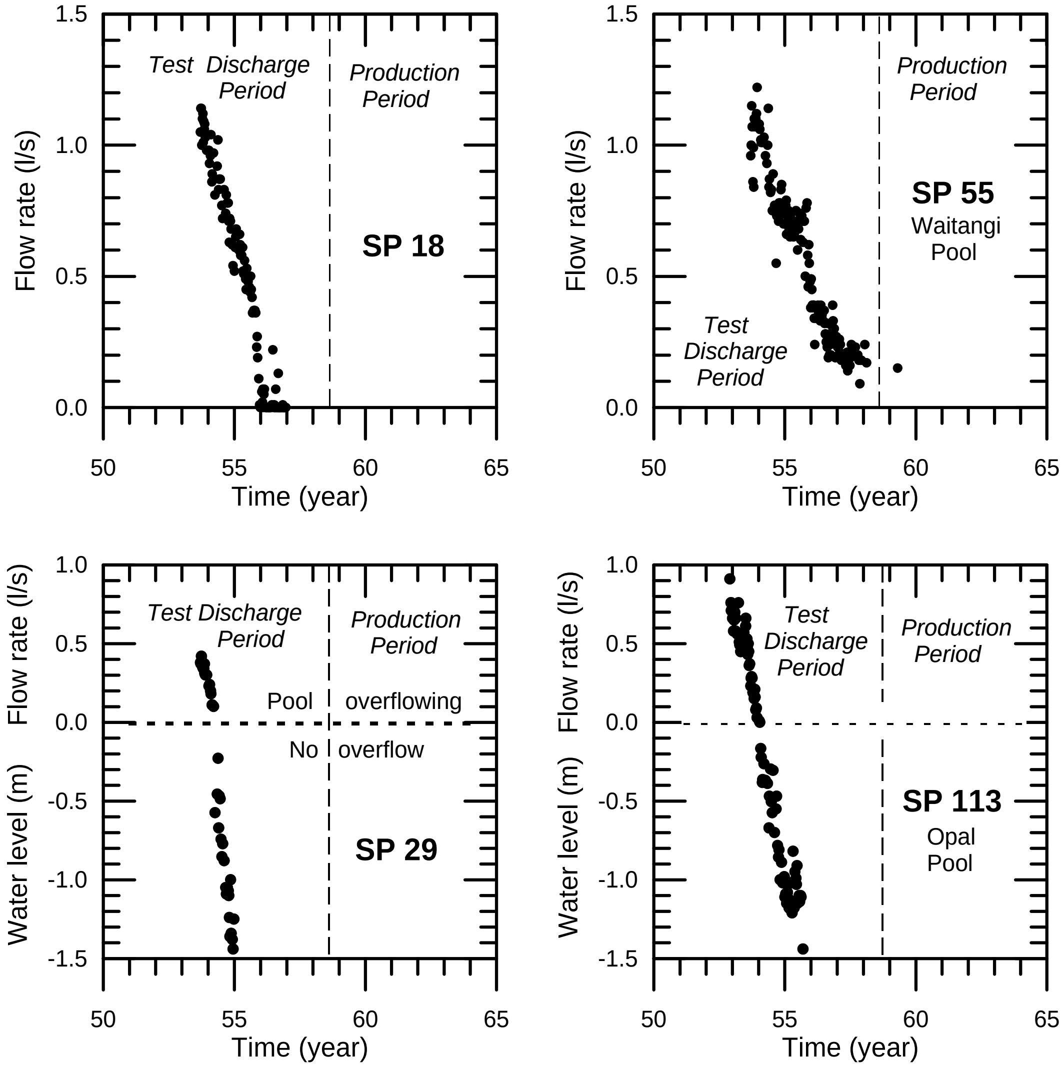


FIGURE 5: Examples of changes with time in overflow rate and water level for thermal features at Wairakei geothermal field resulting from development; note the rapid and linear declines in flow rate. Taken from Glover & Hunt (1996)

Decrease in chloride content of springs

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

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

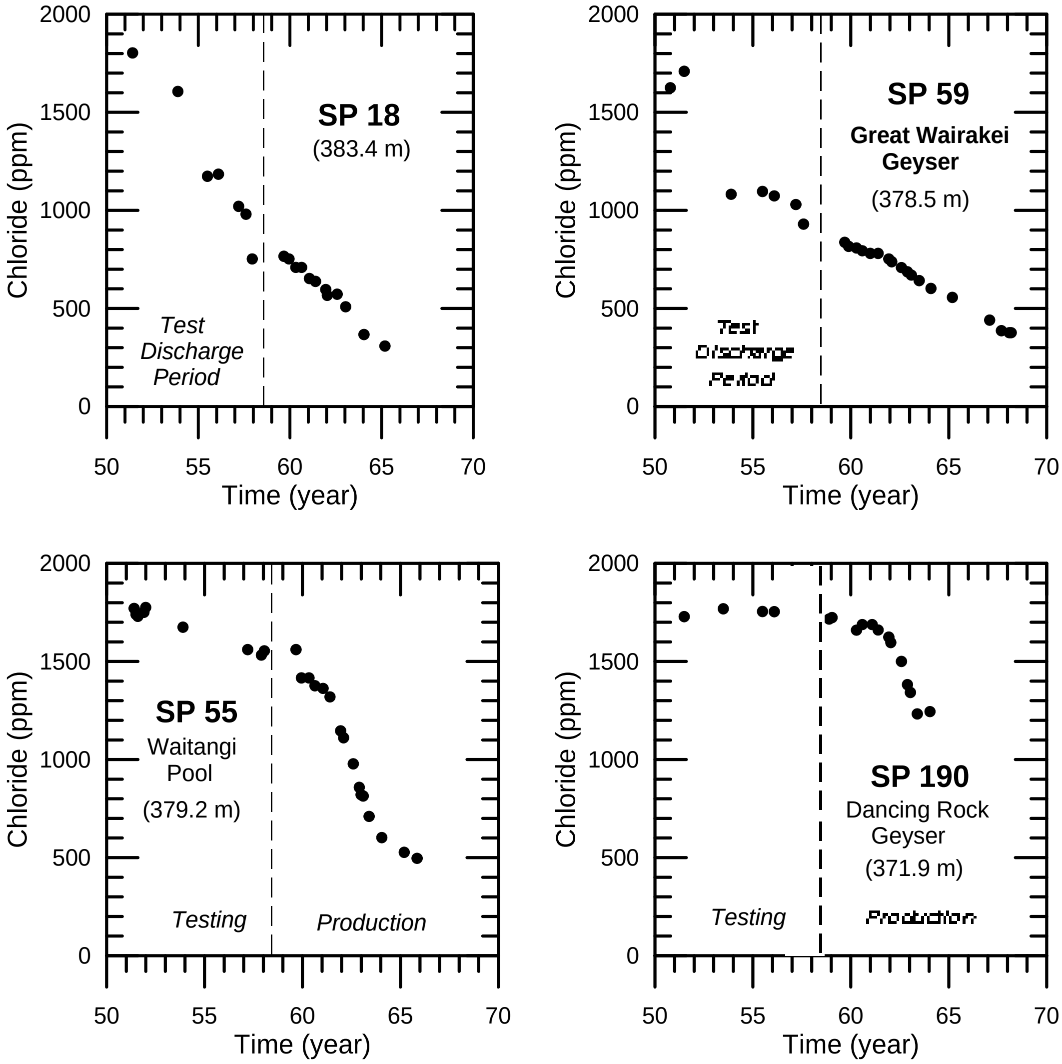


FIGURE 6: Changes with time in chloride content of water in thermal features at Wairakei geothermal field, as a result of development; taken from Glover & Hunt (1996)

Increase in eruption period of geysers

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

Decrease in temperature of springs and pools

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

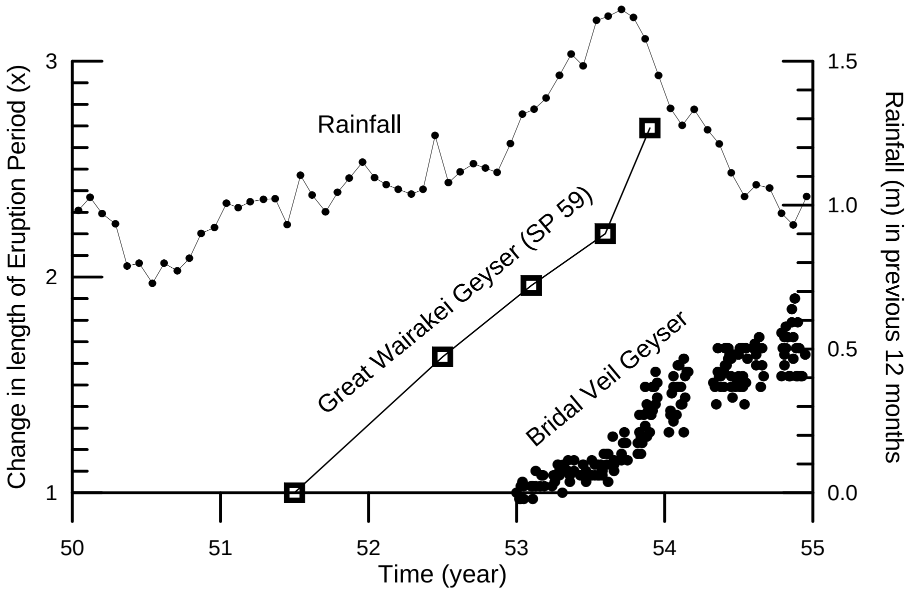


FIGURE 7: Changes in length of eruption period (T/T_0) of geysers in Geyser Valley at Wairakei during the test discharge period; periods are normalised to T_0 = 12.5 hours for Great Wairakei Geyser, and 39 min for Bridal Veil. Rainfall data are monthly running totals of rainfall in previous 12 months.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

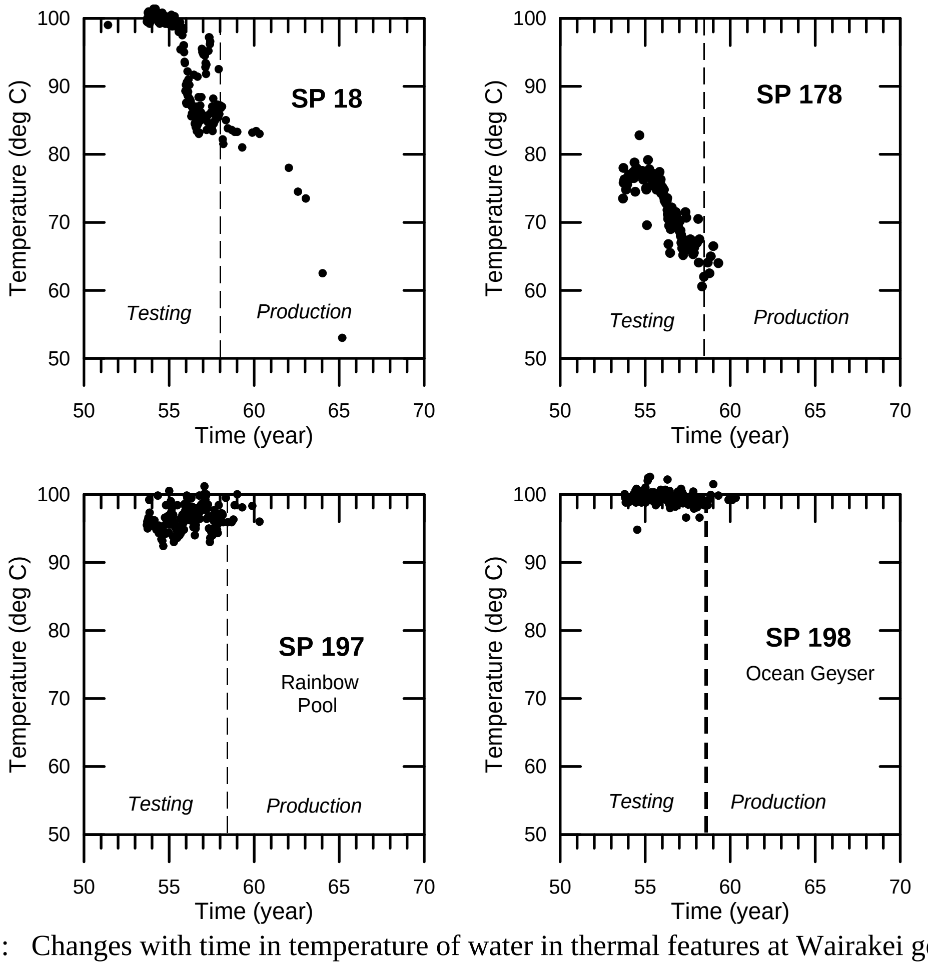


FIGURE 8: Changes with time in temperature of water in thermal features at Wairakei geothermal field, as a result of development; note the different behaviours – the temperature in some features remained near-constant, while in others it fell; taken from Glover & Hunt (1996)

1.3 Groundwater level changes

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

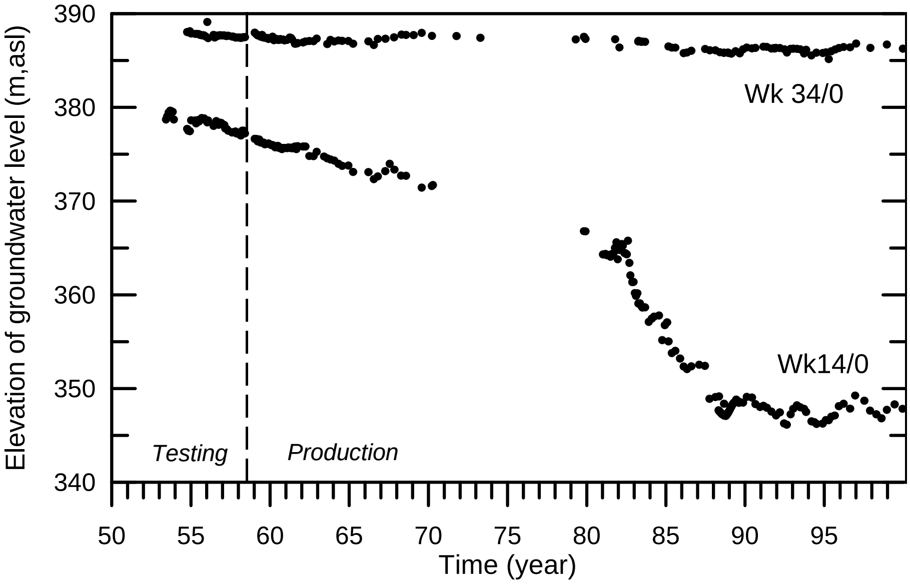


FIGURE 9: Examples of changes in shallow groundwater level in monitor holes at Wairakei

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

1.4 Groundwater temperature changes

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

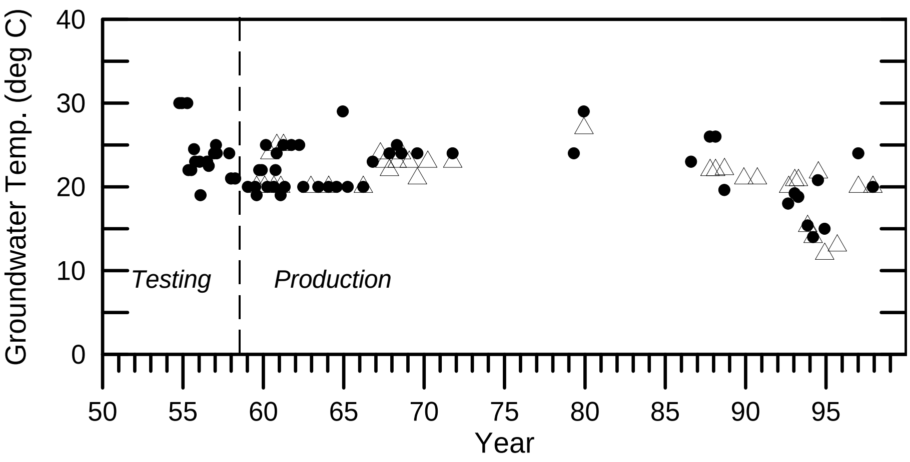


FIGURE 10: Plot of groundwater temperatures in monitor holes outside the production area at Wairakei; note the lack of any significant changes

In monitor holes away from natural thermal features and outside production areas, the groundwater temperature has remained cold (Figure 10).

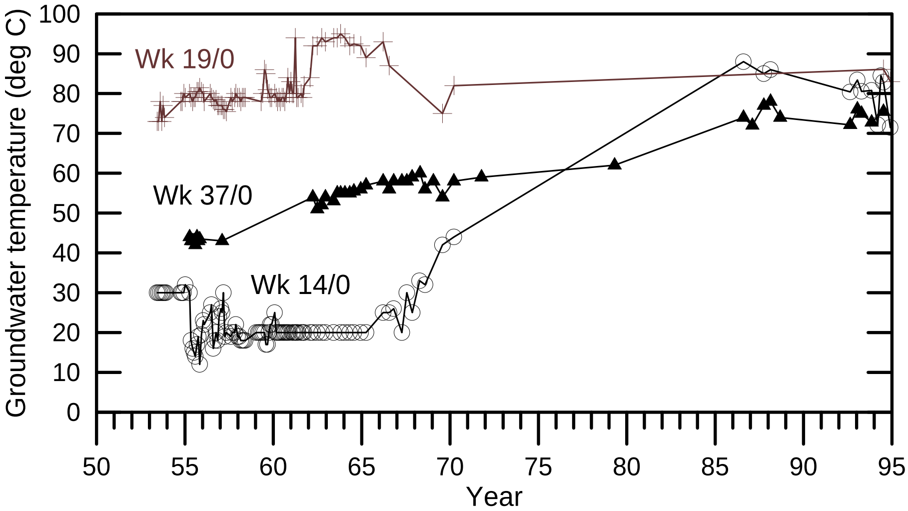


FIGURE 11: Plot of groundwater temperatures in monitor holes in part of the production area at Wairakei; note the increase in temperature in some holes

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

1.5 Changes in surface heat flow

At Wairakei, there have been large but localised changes in surface heat flow associated with exploitation (Allis, 1981). Changes, both increases and decreases, occurred during the test discharge and production periods. In Geyser Valley the heat flow reaching the Wairakei Stream from springs and geysers decreased steadily from 52 MWt in 1952 to 30 MWt in 1958, and to 5 MWt in 1966 when measurements ceased; this decrease reflecting the decline of the natural thermal features. In the Karapiti thermal area, an outbreak of fumarolic activity and hydrothermal eruptions began in 1954, and the heat flow increased from 40 (1950) to 90 MWt (1958). Measurements at Karapiti showed that after production began the heat flow there increased rapidly to a peak of 420 MWt (1964) then declined to about 220 MWt (1979-88) (Figure 12). This increase resulted in an expansion of the area of thermal ground, which caused trees and other temperature-sensitive vegetation to die. However, it also allowed some rare species of thermophilic vegetation (mosses, shrubs) to capitalise on the expansion of thermal area. Hydrothermal eruptions from craters of up to 25 m diameter occur spasmodically every 1-2 years (Figure12), and fumarolic activity continues. The centres of thermal activity appear to migrate randomly. The area is now a major tourist attraction, but the thermal features are insignificant compared with that of Geyser Valley before production began.

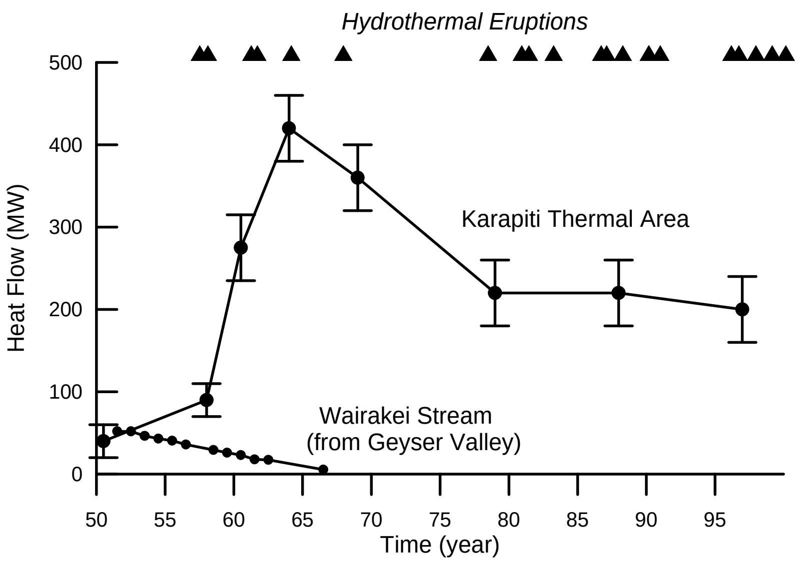


FIGURE 12: Changes in heat flow from the major thermal areas of Wairakei field; taken from Hunt et al. (1998)

1.6 Ground movements

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

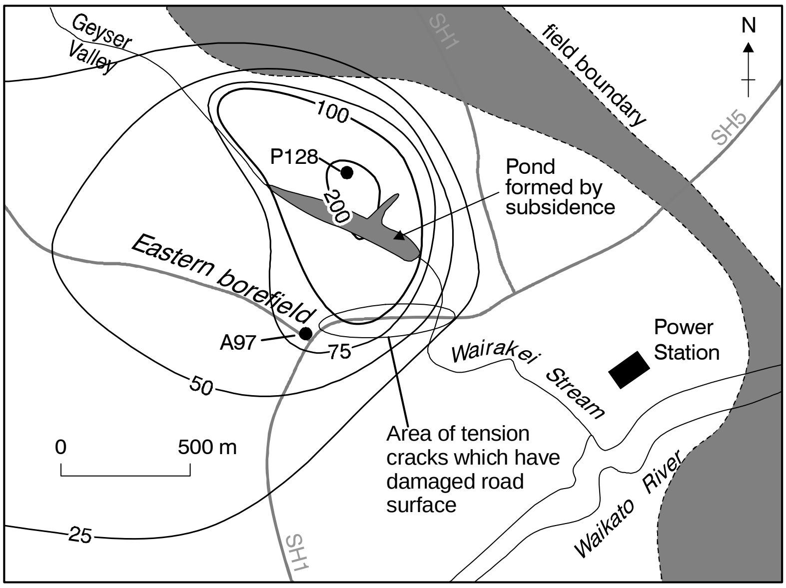


FIGURE 13: Subsidence rates in the main subsidence bowl at Wairakei, rates are in mm/yr for the 1990's; note that the maximum subsidence does not coincide with the borefield. Taken from Allis (2000)

Vertical movements

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

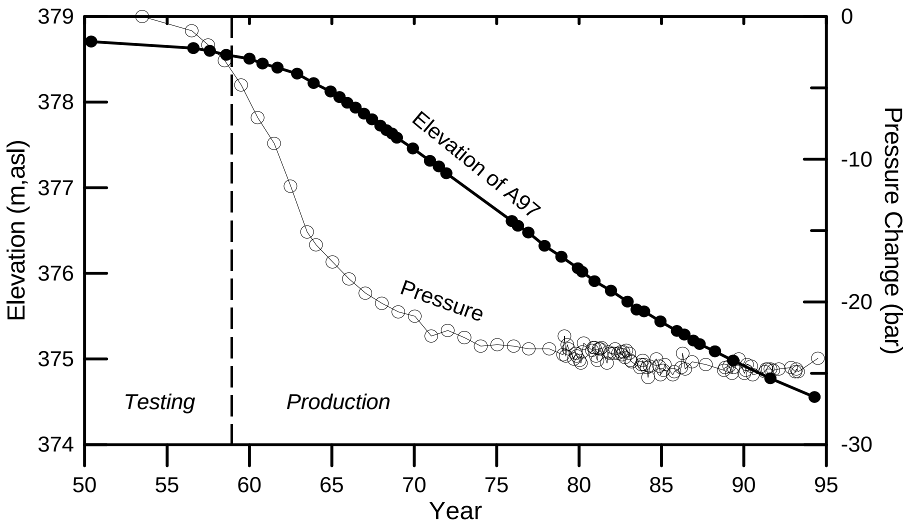


FIGURE 14: Change in elevation (subsidence) of benchmark A97 compared with deep liquid pressure changes at Wairakei, note that the subsidence has continued despite stabilisation of pressure since late 1970's. Data from Hunt & Glover (1996)

The principal environmental effect of the subsidence has been a change to the profile of the bed of the Wairakei Stream as a result of differential subsidence: once a fast flowing narrow stream, it now has a pond in the area of maximum subsidence. This pond is up to 6 m in depth, and the bottom is filling with silt. Trees that have been flooded have died; but the pond has become a popular habitat for water birds. The subsidence has caused casing damage in wells closest to the main subsidence area: compressed joints and breaks occur at 140-270 metres depth, which defines the vertical section of compaction (Bixley and

Hattersley, 1983). There has been no casing protrusion because the wells are adequately cemented near the surface, and so the compression is manifested at depth by casing deformation.

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

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

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

2.1 Development history

At Ohaaki, drilling began in 1965, and in the following 6 years 25 deep wells were drilled. From the middle of 1967 until the start of 1972, test discharges were conducted during which time the annual mass withdrawal increased to about 10 Mt/yr (Figure 15). During this "Test discharge period" all the fluid withdrawn was discharged into the Waikato River or the atmosphere; there was no reinjection. In the following 16 years, a further 18 holes were drilled but no extensive testing was done; the average mass discharge was only 1.5 Mt/yr and did not exceed 3.5 Mt/yr. This time is known as the "Recovery period". Commissioning of the Ohaaki power station (116 MWe installed capacity) began in August 1988 and was completed in November 1989. Mass withdrawal rose to 16.2 Mt in 1990, and has remained at similar values since then (Figure 15). Since commissioning, most of the waste fluid has been reinjected (mainly around the periphery of the production areas) and net mass loss has been about 6 Mt/yr.

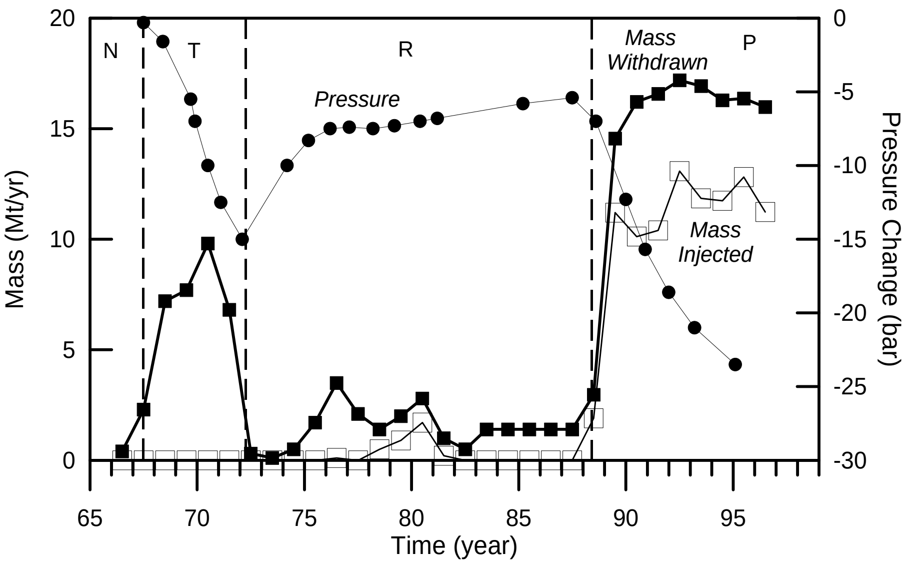


FIGURE 15: Variation of mass withdrawal (solid squares), reinjection (open squares), and deep liquid pressure (solid dots) with time at Ohaaki geothermal field. N = Natural state, T = Test discharge period, R = Recovery period, and P = Production period; taken from Glover et al. (2000)

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

2.2 Pressure changes

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

2.3 Changes to natural thermal features

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

Prior to exploitation the Ohaaki Field had few natural thermal features (cf. Wairakei); the largest and most significant feature being the Ohaaki Pool, a boiling pool with a surface area of about 850 m^2. This pool has cultural significance for the local Maori people, and is noted for its beautiful fretted sinter lip and surrounding sinter apron.

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

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

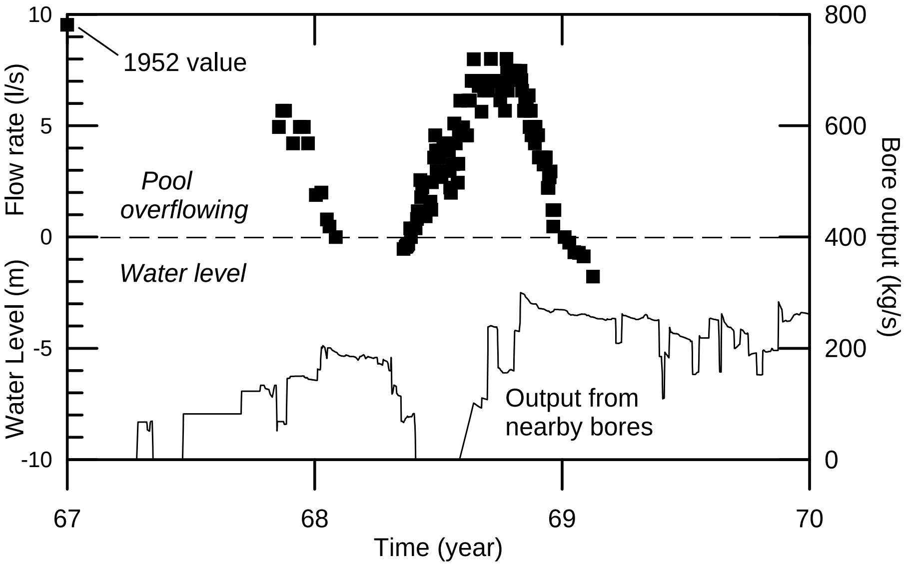


FIGURE 16: Plot showing variation of flow rate and water level in Ohaaki Pool during the early part of the test discharge period at Ohaaki field; note the rapid response of flow rate to changes in output from nearby bores being test discharged. Taken from Glover et al. (2000)

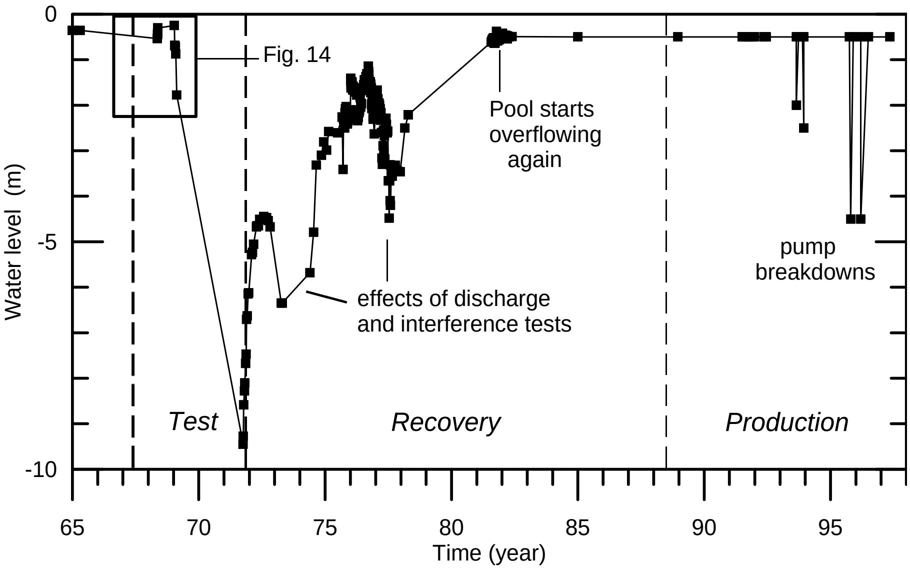


FIGURE 17: Plot showing variation of water level in Ohaaki Pool with time; note the rapid recovery of water level after end of the test discharge period. Taken from Glover et al. (2000)

Changes in temperature of Ohaaki Pool

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

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

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

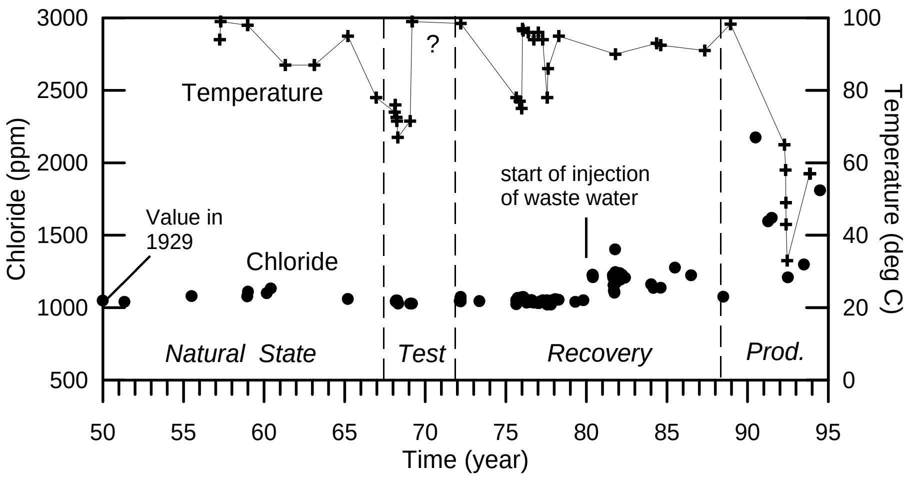


FIGURE 18. Changes in temperature and chloride concentration in Ohaaki Pool; note the lack of change in chloride concentration until after injection of waste water began. Taken from Glover et al. (2000)

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

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

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

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

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

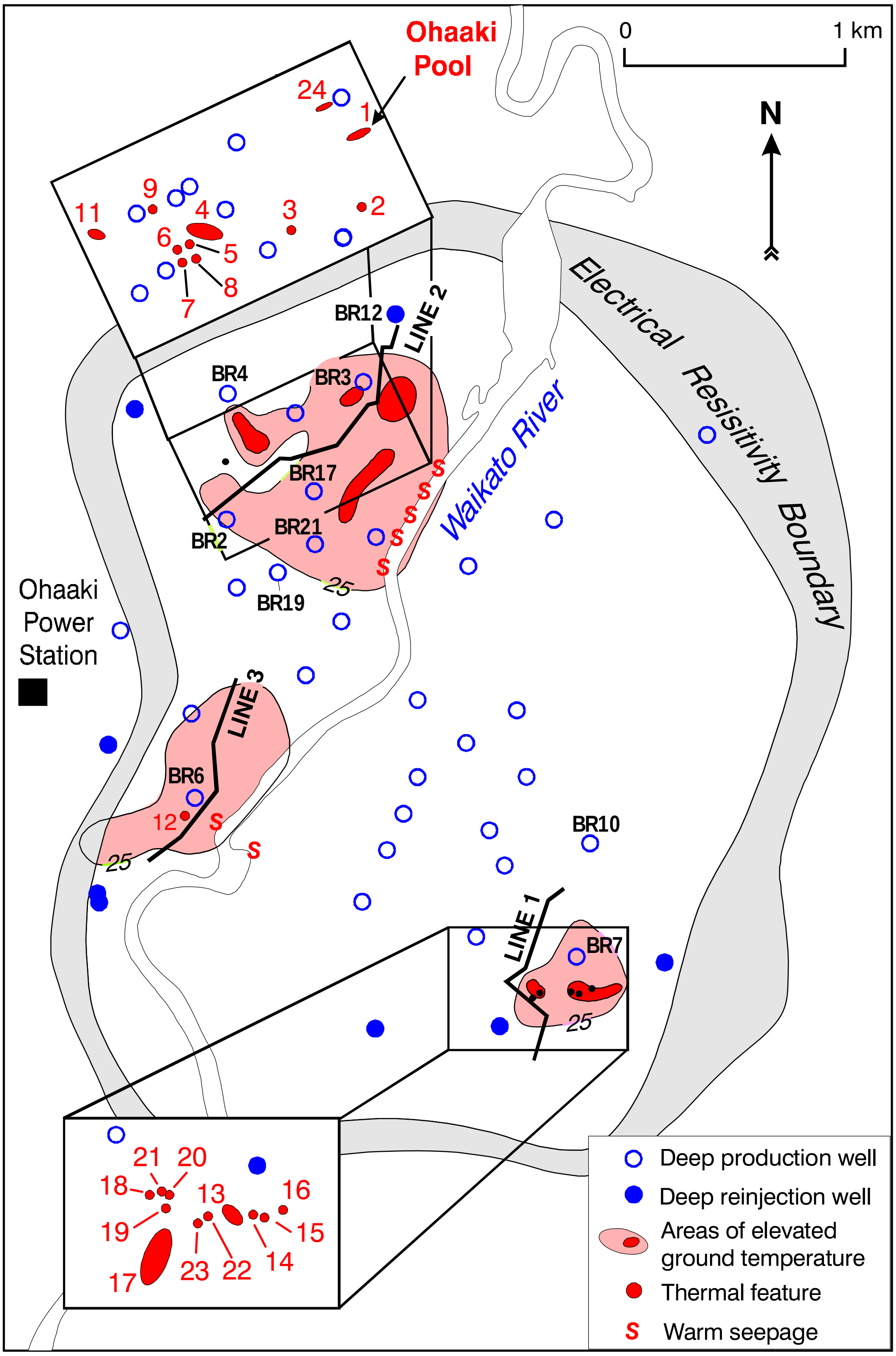


FIGURE 19: Map of Ohaaki geothermal field showing location of thermal features and ground temperature survey lines; taken from Hunt & Bromley (2000)

2.4 Ground movements

Pressure drawdown in the reservoir during the test discharge period and since production began has led to compaction within a rock unit above the reservoir, resulting in deformation of the ground surface over a kidney-shaped area in the north-western part of the field (Clotworthy et al., 1995; Allis et al., 1997) (Figure 20). The deformation is associated with draining of fluid from a compressible lacustrine mudstone unit of limited areal extent, but up to 250m thick.

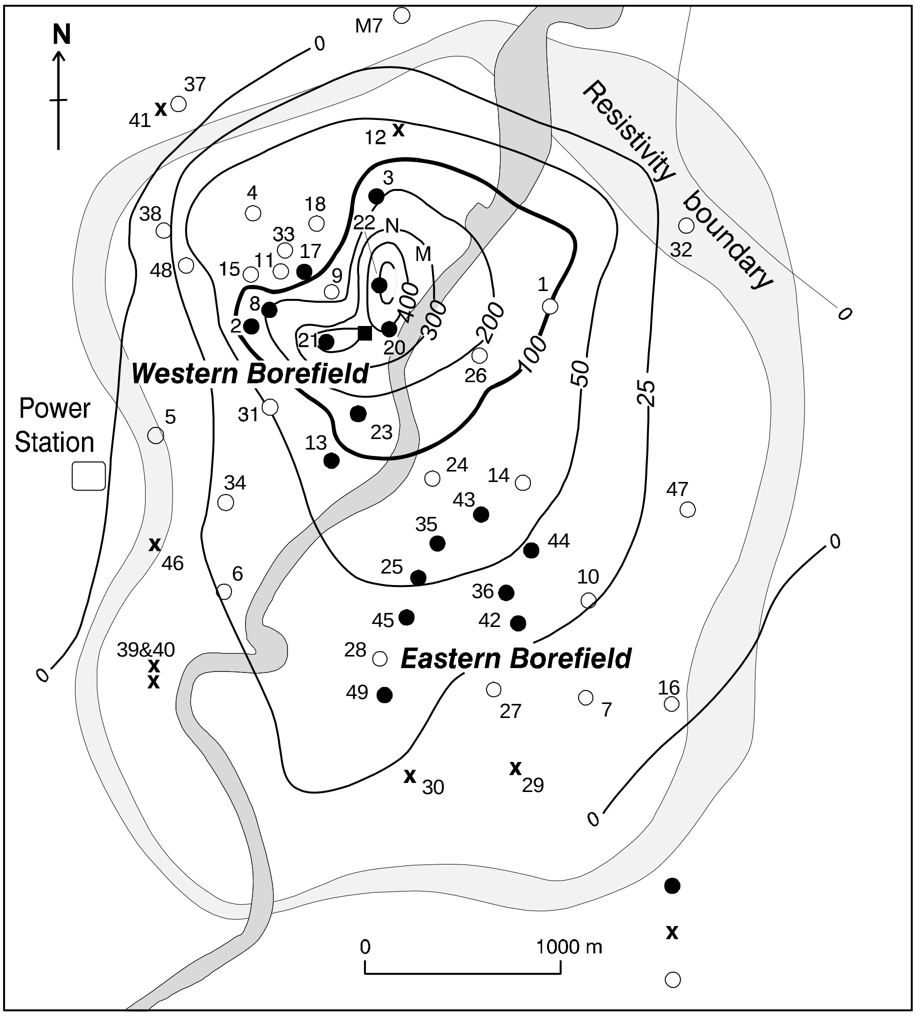


FIGURE 20: Map of Ohaaki geothermal field showing ground subsidence rates during the production period; numbers indicate well numbers; rates are for the period 1993-95. Note the kidney shape of area of greatest subsidence rate. Taken from Allis et al. (1997)

Subsidence monitoring shows that during the test discharge period the centre of the area subsided by 0.15-0.20 m. There was little subsidence during the recovery period, but it restarted at the beginning of the production period and by January 1995 had exceeded 1.2 m (Figure 21). The subsidence has resulted in tilting which has caused water in the Ohaaki Pool (when full) to overflow from the south-western part of the pool in addition to the drainage channel.

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

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

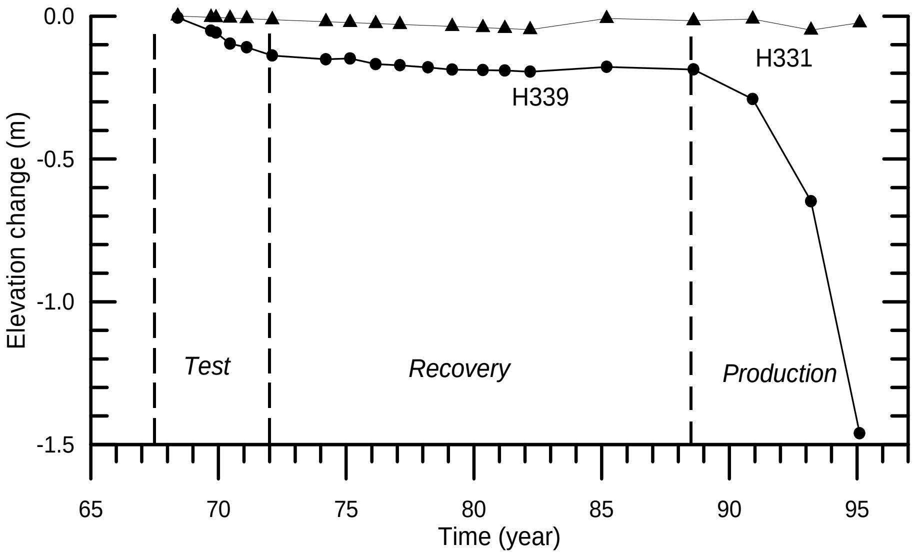


FIGURE 21: Elevation changes at selected benchmarks in Ohaaki field, benchmark H331 (triangles) lies outside the field, and H339 (solid dots) is near the centre of the subsidence bowl. Note that subsidence stopped soon after end of test discharge period, and recommenced shortly after start of the production period. Taken from Glover et al. (2000)

2.5 Ground temperature change

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

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

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

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

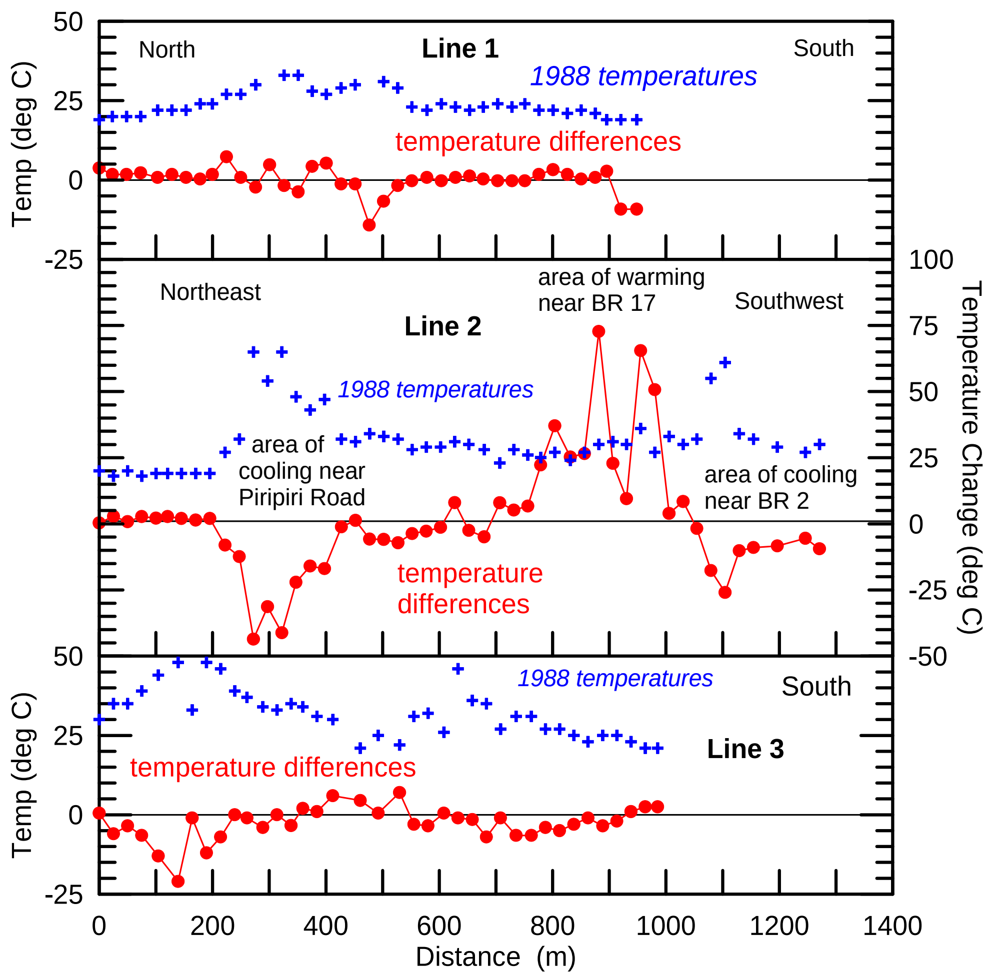


FIGURE 22: Changes in shallow ground temperatures at Ohaaki field, temperature differences are for the period 1988-1996, and cover the first 8 years of the production period. The differences have been adjusted for seasonal differences; location of the survey lines are shown in Figure 19. Taken from Hunt & Bromley (2000)

2.6 Groundwater level changes

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

2.7 Groundwater temperature changes

The temperatures at, or near the water surface, have been measured; in 13 shallow groundwater monitor holes since the test discharge period. Subsequently, more monitor holes have been drilled, and at present measurements are made in 46 monitor holes. Over most of the field the groundwater is cold (ambient temperature 10-25°C), but in two areas which surround known areas of thermal ground the groundwater temperature is warm (25-75°C) or hot (75-100°C).

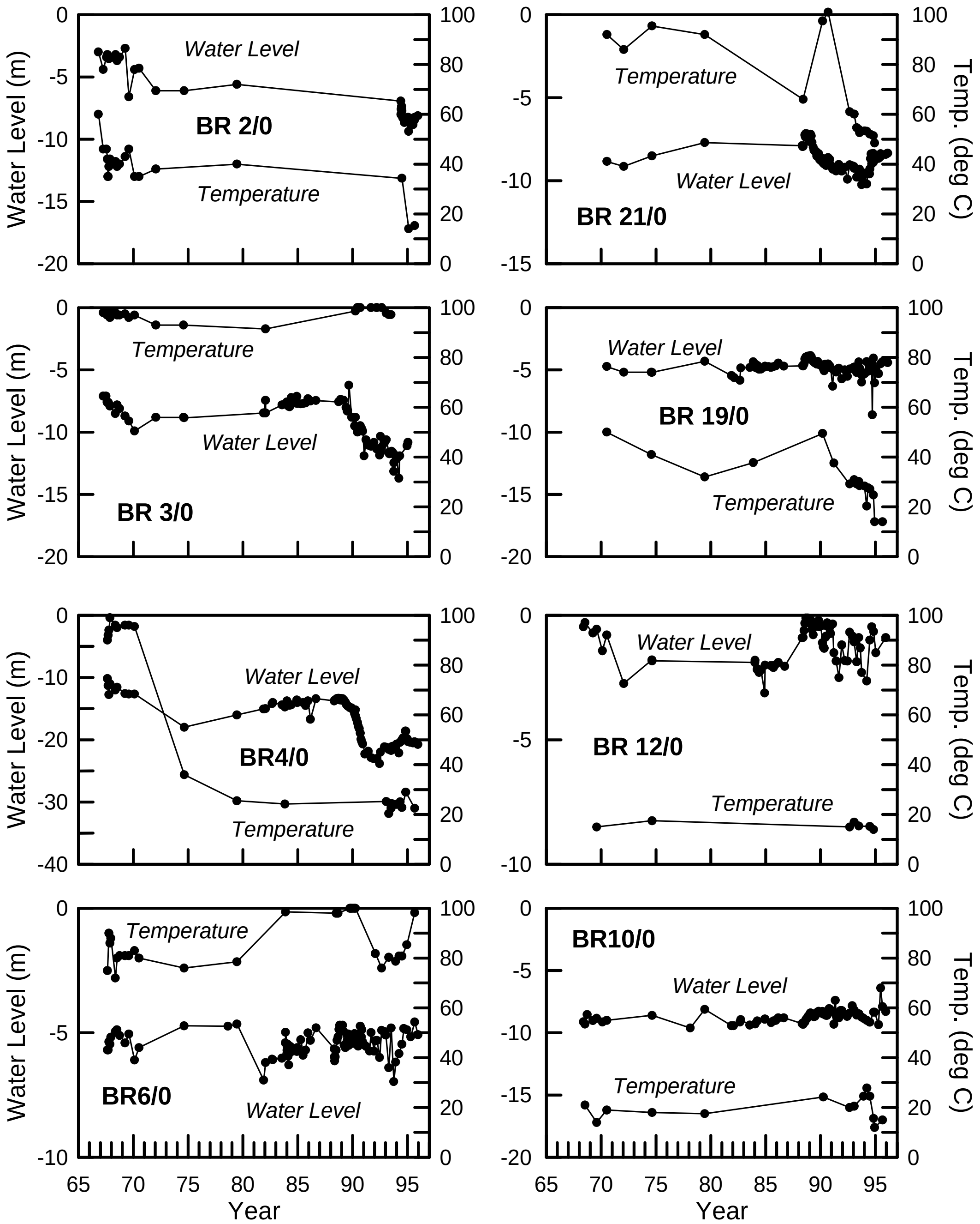


FIGURE 23: Graphs of change with time in shallow groundwater level and groundwater temperature at Ohaaki field; taken from Hunt & Bromley (2000)

The monitoring has shown that generally the test discharges had no effect on shallow groundwater temperatures, either hot (e.g. BR3/0,BR6/0; Figure 23) or cold (e.g. BR10/0; Figure 23). One clear exception, however, was in BR4/0: between August 1967 and February 1970, the groundwater was near boiling (90-100°C), but between then and August 1974 the temperature decreased by about 60°C and has remained at 20-25°C since June 1979 (Figure 23). This decrease in water temperature may reflect the onset of a localised cold downflow associated with the pressure drop that occurred during the test discharge period. As the hot water drained downwards it was replaced by cold groundwater which moved in laterally.

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

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

2.8 Seismic activity

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

3. CHANGES AT ROTORUA GEOTHERMAL FIELD (NEW ZEALAND)

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

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

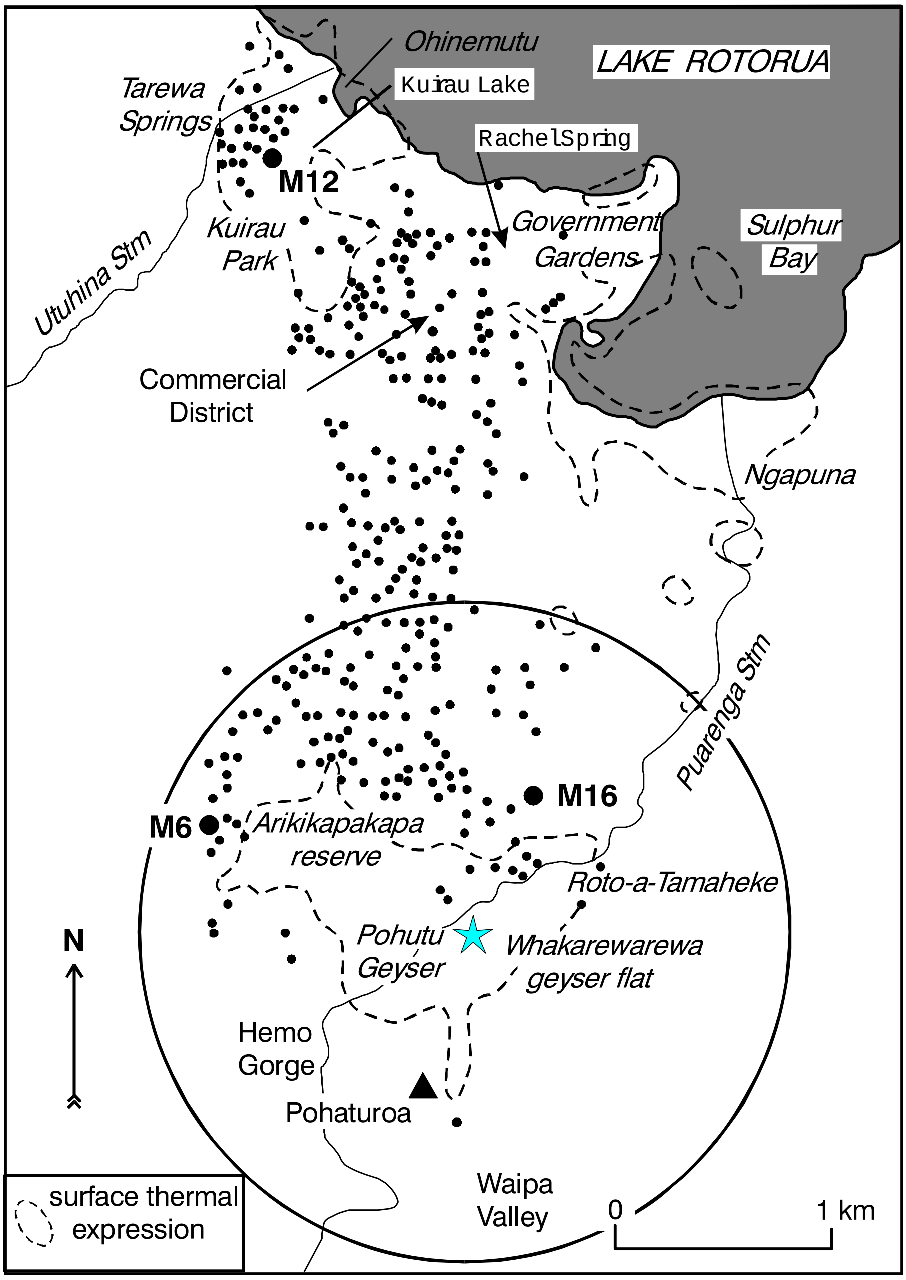


FIGURE 24: Distribution of geothermal wells in Rotorua City in 1985 (solid dots), monitor wells and thermal areas (outlined by broken lines); circle shows area in which all geothermal wells were closed. Taken from Scott & Cody (2000)

3.1 Exploitation and management history

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

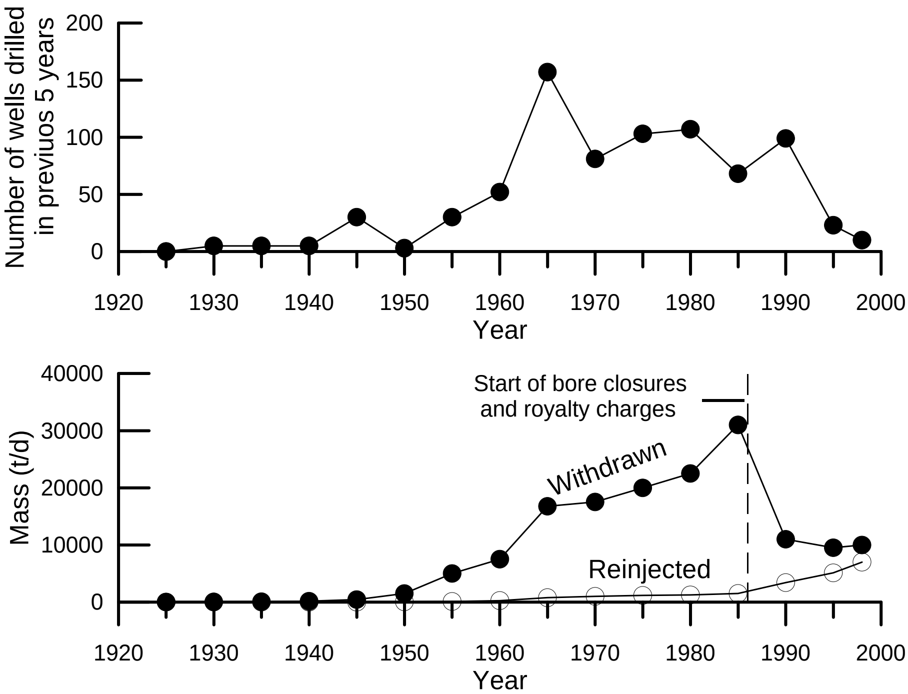


FIGURE 25: History of wells drilled in Rotorua, and the amounts of fluid withdrawn and reinjected; note the rapid decrease in mass withdrawn and increase in mass reinjected following the start of bore closures and imposition of royalty charges. Data from Scott & Cody (2000)

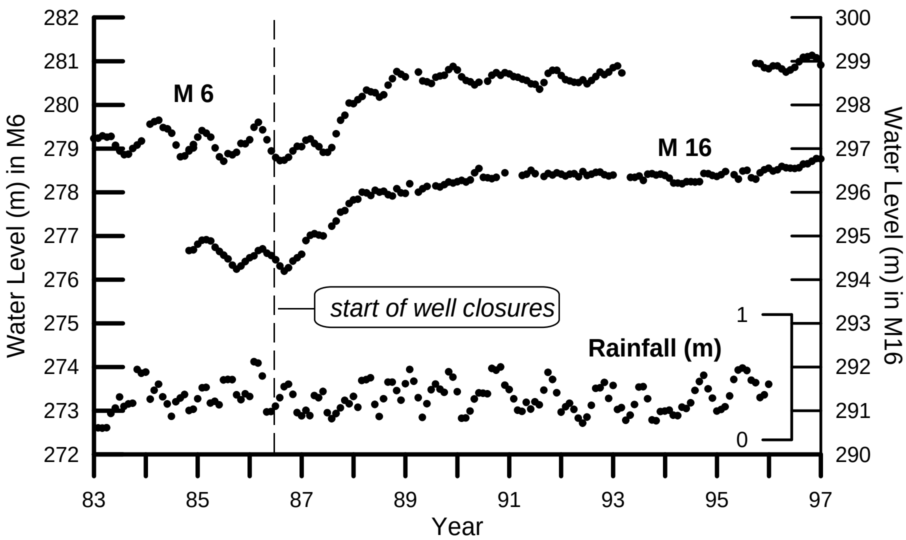


FIGURE 26: Changes in water level in some monitor wells in Rotorua City; location of the wells is shown in Figure 24. Note the rise in water level following start of bore closure programme. Data from Scott & Cody (2000)

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

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

3.2 Changes in field pressure and water level

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

3.3 Changes to surface thermal features

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

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

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

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

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

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

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

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

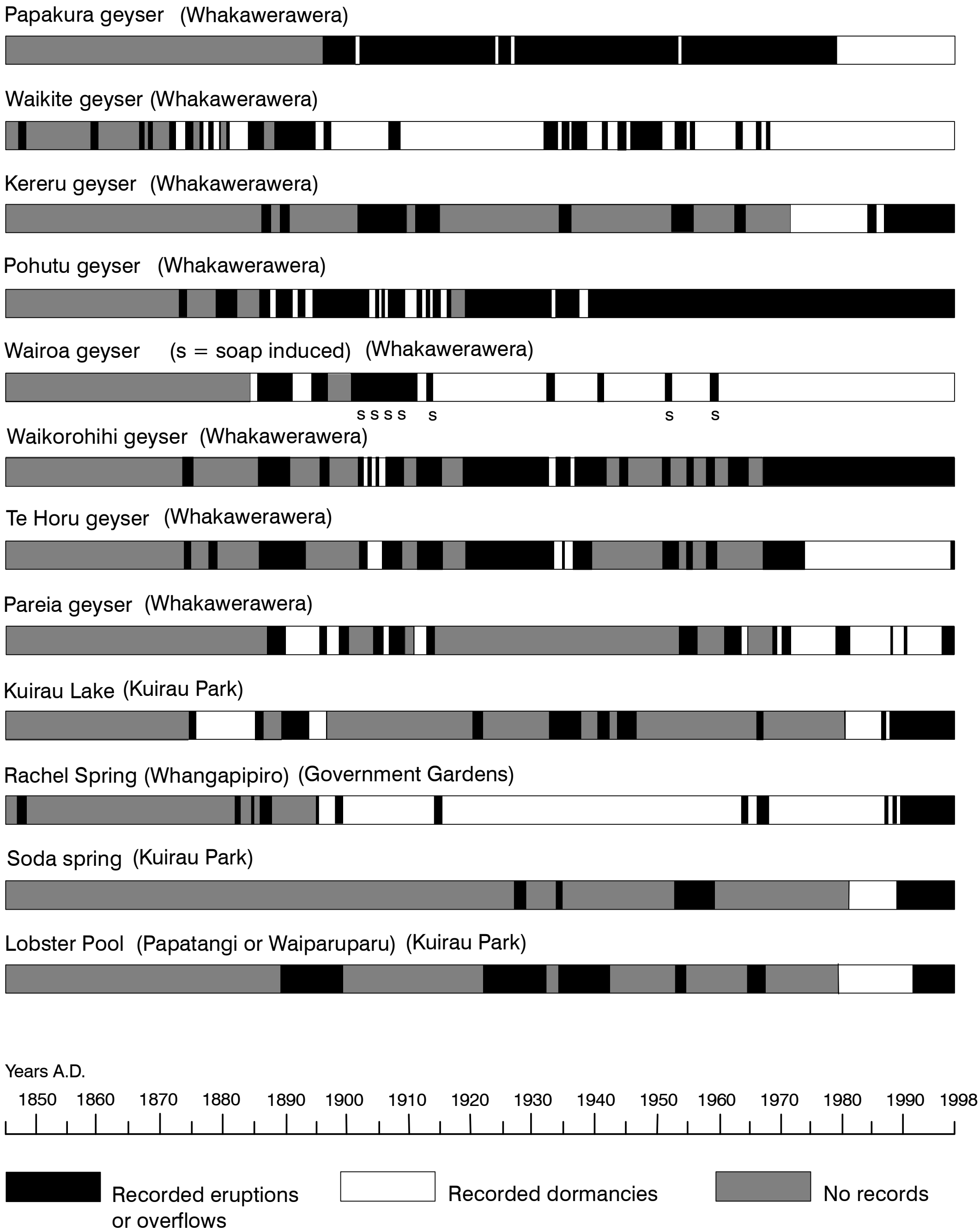


FIGURE 27: Histograms showing historic changes in activity for some major spring and geysers in Rotorua City; taken from Scott & Cody (2000)

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

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

Parekohoru Spring: In 1985-86, this spring ceased overflowing for several days each winter; the first such stoppages known in historical times. Since 1988 there have been no further cessation of flows. Boiling surges with large overflows recommenced in 1995, similar to reports of earlier this century, and continues to date.

Rachel Spring: This is the sole remaining boiling and flowing alkaline spring in the Government Gardens. Prior to 1987, the last recorded overflowing and boiling episode was in 1967. From then until 1987 its water level had remained at 1.2-1.7 m below overflow, and the temperature at 70-80°C. However, since late 1988 it has been continually boiling and flowing at 7-12 l/s. It still has brief cessation of overflow, but these stoppages last only a few days and since 1988 its water level has never fallen more than 0.1 m below overflow.

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

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

Hydrothermal eruptions

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

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

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

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

4. CHANGES IN TONGONAN GEOTHERMAL FIELD (PHILIPPINES)

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

The chemistry of the Tongonan thermal springs was first determined in 1965. Surveys were also conducted in 1973 and 1979 prior to exploitation. After six years of drilling and discharge testing an assessment of the response of the thermal springs was made, but no significant changes in discharge chemistry of the springs was found. In 1983, a monitoring programme to measure any effects of exploitation on the thermal features in the GTGF was started.

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

Prior to development, the springs discharged neutral-pH chloride waters with 2500-4000 mg/kg of Cl, l50-180 mg/kg HCO_3, and 40-80 mg/kg SO_4. The major cations include Na (650-1400 mg/kg), K (42-107 mg/kg) and low Ca (12-48 mg/kg). Trace amounts of Mg and Fe are also present in less than 1.0 mg/kg. Assuming maximum steam loss at 100°C, the quartz geothermometer predicts temperatures of 160 -180°C for the reservoir feeding the springs. The chemistry suggests the Bao-Banati springs mark the outflow sector of the field.

4.1 Flowrate changes

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

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

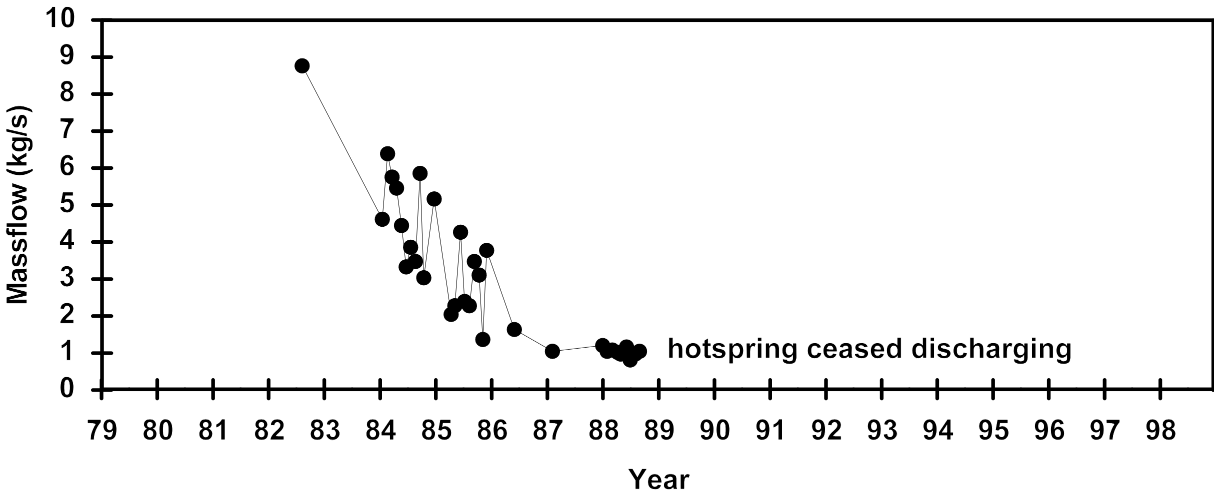


FIGURE 28: Changes in mass flowrate of hot spring no. 16 with time, Tongonan, Philippines; taken from Bolanos & Parilla (2000)

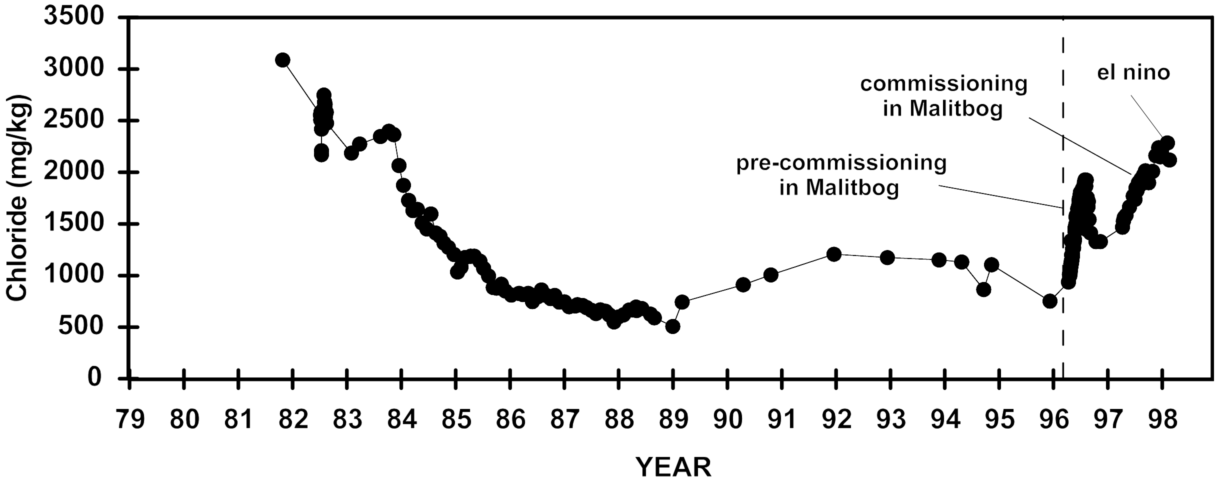


FIGURE 29: Changes in chloride concentration in hot spring no. 1 with time, Tongonan, Philippines; taken from Bolanos & Parilla (2000)

4.2 Chemistry changes

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

During 1990-1995, a temporary increase in chloride concentration of the springs was observed. This can be attributed to the increase in brine reinjection at Tongonan 1 as a consequence of declining well enthalpies and increasing generation during the period. The increase in reinjection temporarily increased reservoir pressures, and effectively increased the contribution of deep geothermal fluids to the spring discharges. However, in 1995 chloride concentrations in spring waters appear to have declined as reinjection in Tongonan decreased. This suggests the absence of reinjection fluid breakthrough coming from the Mahiao-Sambaloran reinjection sink, which had chloride concentrations of 12500-16000 mg/kg.

During the pre-commissioning activities in the Malitbog Sector in May-August 1996, an increase in

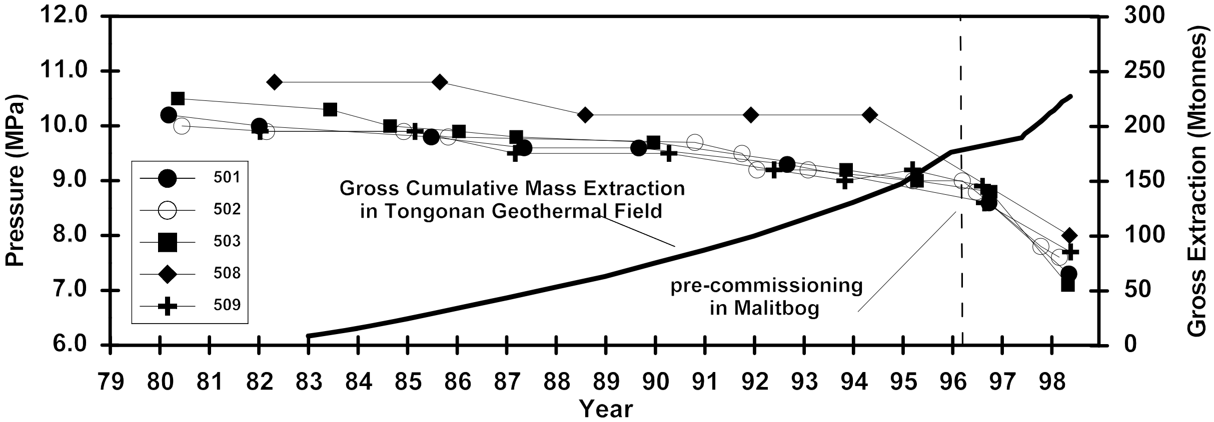


FIGURE 30: Deep pressure changes in nearby Malitbog wells (symbols) and cumulative gross mass extraction from Tongonan geothermal field (solid line); pressure changes are at reference depth of -1000 m RSL. Taken from Bolanos & Parilla (2000)

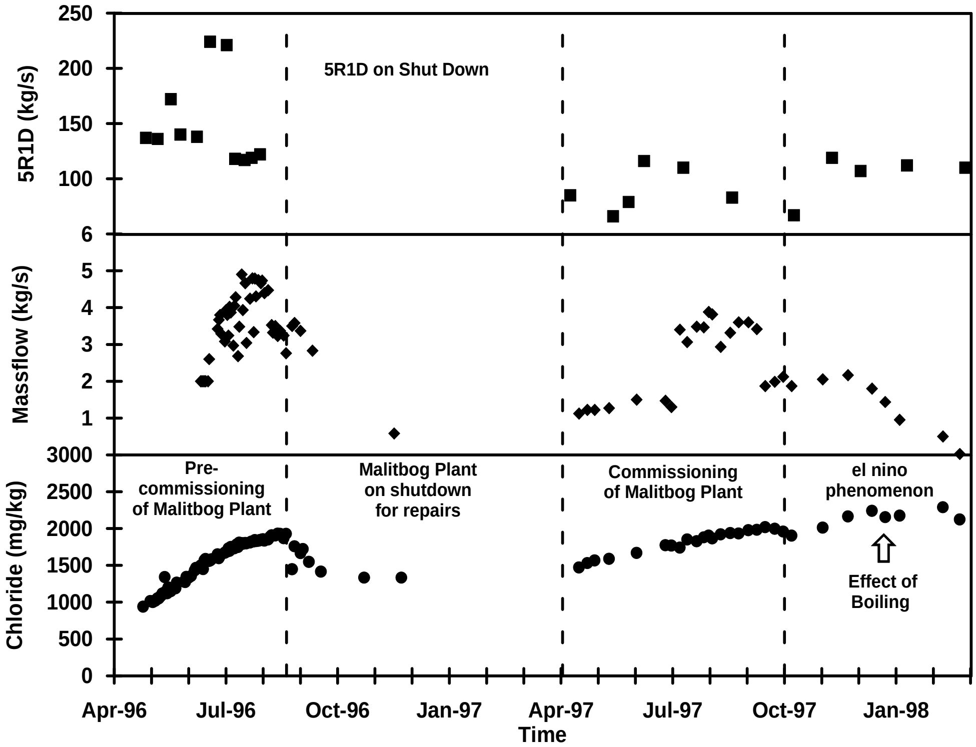


FIGURE 31: Relation between rate of reinjection into well 5R1D, and changes in massflow rate and chloride of hot spring no. 1; taken from Bolanos & Parilla (2000)

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

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

4.3 Changes in quartz geothermometer temperatures

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

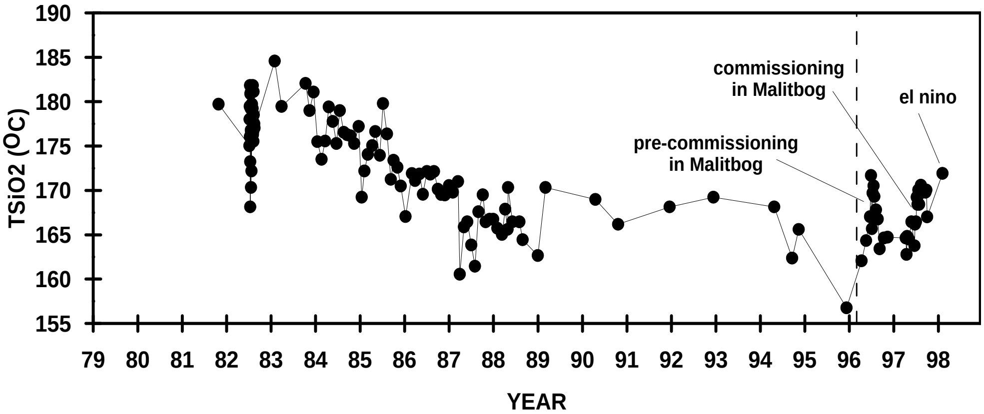


FIGURE 32: Changes in quartz geothermometer temperatures of hot spring no. 1

Monitoring of the Bao-Banati thermal springs during operation of Tongonan 1 Power Plant shows there have been:

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

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

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

5. CHANGES AT PAMUKKALE (TURKEY)

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

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

- Outgassing of CO_2 from water in the pools decreases its travertine depositing capacity;
- Swimmers in the pools leave organic relicts which cause a rapid growth of algae, which cause a change in colour of the travertines.

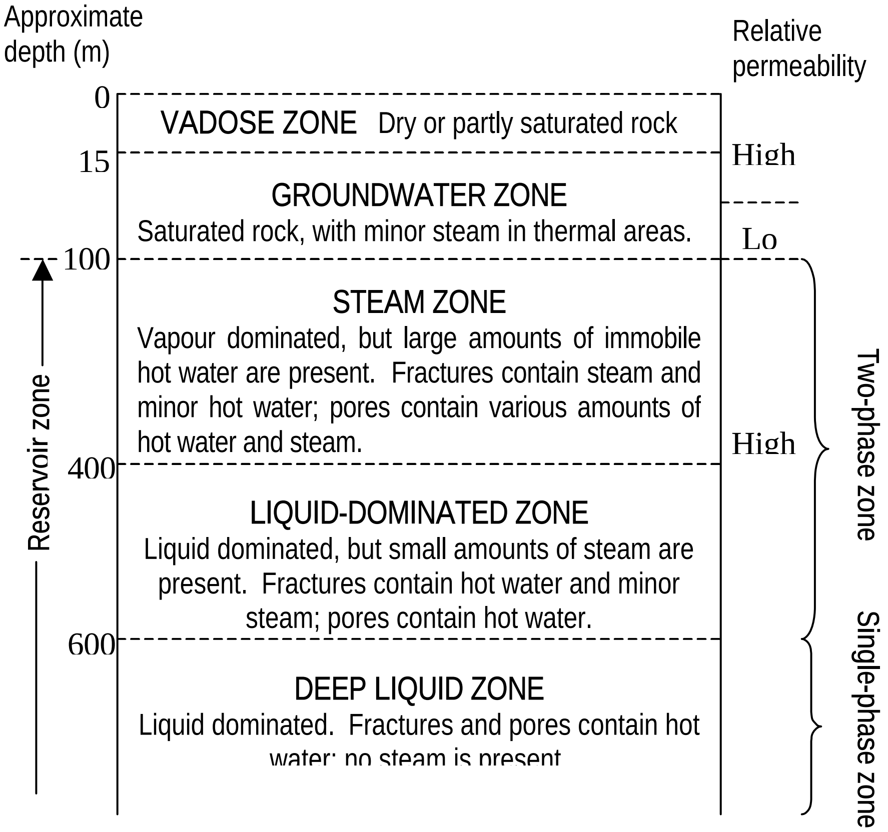
The lack of a sewage system is another major source of pollution. Each hotel has a septic tank dug into the travertine and, although lined with cement, they leak waste water which emerges at the bottom of the terraces. There are large amounts of algae in these places because the leaked water is rich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

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

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

APPENDIX I

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



The United Nations University
GEOTHERMAL TRAINING PROGRAMME

Hunt, T.M.: Five lectures on environmental effects of geothermal utilization
Reports 2000
Number 1, 51-60

LECTURE 3

MONITORING

1. REASONS FOR MONITORING

1. To obtain data on which rational and informed resource management decisions can be made by developers and regulatory authorities;
2. To verify that management decisions are having the desired outcomes;
3. To enable the public to have confidence in the environmental management process;
4. To assist in building up a knowledge of geothermal systems and how to develop them in an environmentally responsible way.

2. PRINCIPLES OF MONITORING

2.1 Basic principles

- Monitoring needs to *begin before development starts* so that a good baseline can be obtained. It is not possible to go back in time, so many different eventualities need to be considered and a *fully integrated monitoring programme needs to be developed* and begun well before large scale productions starts.
- Monitoring should be conducted at a *frequency sufficient to enable natural variations to be distinguished* from exploitation-induced changes.
- The data collected needs to be interpreted and *regularly compared with pre-determined "trigger points"*. "Zero change" is just as important as a change, and is not a valid reason for stopping monitoring, although the frequency of measurement may be reduced after a long period of no change.
- *Data needs to be reliable.* Equipment should be calibrated regularly and operated by a competent person.

2.2 Monitoring programme planning

In setting up a monitoring programme it should be recognised that:

- The programme is likely to extend for several years and/or even decades, therefore all observations and measurements need to thoroughly documented in a suitable archive.
- During this time there will probably be staff changes and therefore there needs to be a written set of instructions about how and when measurements will be made, so that measurements are compatible with each other
- The programme is likely to need revision from time to time

2.3 General requirements

Important factors in monitoring are:
- Care needs to be taken in making the measurements to obtain the greatest accuracy. Instruments should be calibrated before each survey, and the measurements must be made by a competent

operator who is fully aware of the reasons for making the measurements.

- Where possible, the same instruments and observation techniques should be used in all the surveys to minimise errors.
- If possible, the person interpreting the measurements should have made the measurements or have been involved in the surveys.
- Monitoring sites need to be clearly marked and monitoring facilities (e.g. groundwater monitor wells) need to be maintained.

3. MONITORING OF NATURAL THERMAL FEATURES

Natural thermal features are rare and often have significant cultural and economic value. Furthermore, experience of changes to natural thermal features as a result of geothermal developments has shown that they can be very fragile.

3.1 Geysers

The activity of a geyser is generally quantified by the *eruption period*, which is the length of time between the start of successive eruptions. For many geysers this is relatively uniform over periods of weeks or months; in one famous geyser, Old Faithful Geyser in Yellowstone National Park (USA), the eruption period has been stable for at least 150 years. For most geysers however the eruption period will change with time due to rainfall and supply of water. During the time of exploration drilling and discharge testing of drillholes in Wairakei field (1950-1958) the eruption period of Bridal Veil Geyser (Spring 199) in nearby Geyser Valley increased from about 38 min. in Nov. 1952, to about 55 min. in Dec. 1953, to about 65 min. in Dec. 1954 (Figure 5). During the test discharge period the eruption period of Great Wairakei Geyser (Spring 59) increased from about 12 to more than 30 hrs, before it stopped geysering in 1954 (Figure 5). Comparison of the eruption period data with rainfall measurements (Figure 5) showed that these increases in eruption period were not caused by a decrease in rainfall (Glover & Hunt, 1996).

A common method of reliably measuring eruption period is to install a water temperature sensor (thermocouple) in the outflow channel from the geyser apron, connected to a data logger with an internal clock. Eruption of the geyser soon causes water to flow in the channel. The sensor in the channel detects this water, and a signal is sent to the data logger. The sampling frequency of the data logger can be matched to the eruption period; for geysers with long eruption periods (> 1 day) a sample may be only every 10 minutes, but for those with a shorter period a sample every minute may be necessary. The data may be corrupted by periods of splashing prior to full eruption, but this can be minimised by careful selection of the site of the sensor. Setting up such a recording device may involve some trial and error placement of the sensor(s) and the selection of an appropriate sampling interval. Such equipment is readily available commercially and costs about US$1000-2000 depending on the degree of sophistication, inclusion of software, and number of sensors. The equipment is easily portable and requires only dry-cell or automobile batteries.

Length or duration of play can also be measured with the above equipment, but this is often more difficult to determine because for most geysers the cessation of eruption is not a sharp event; eruptions generally die away gradually.

Eruption height can also be measured, but this may be difficult because the liquid in the eruption column can be obscured by steam clouds. Generally, eruption height is measured by vertical triangulation using a theodolite. Sophisticated equipment such as a recording infra-red camera which enable the steam cloud to be penetrated are not necessary for the purposes of geothermal development monitoring, but are used for studies of geyser eruption processes. For geothermal monitoring purposes a set of (say) 5 measurements of eruption height, every 1-3 months would be adequate.

Another indication of geyser activity is volume of water discharged in each eruption, but in practise this is often difficult to measure unless all the water drains away from the geyser apron through a single channel.

Data from New Zealand suggests that indicators of geysers being affected by geothermal developments are:
1. Increase in eruption period, by more than about 20% (natural variation);
2. Increase in duration of eruptions;
3. Reduction in eruption height.

However, it should be clearly recognised that the characteristics of a single geyser, or groups of geysers, can change naturally with time. Such changes may occur slowly over a period of several years and be associated with changes in rainfall, or may be sudden if associated with earthquake activity that alters the plumbing system of the geyser.

3.2 Hot springs

Parameters of hot springs which indicate the state of health of a spring are:

1. *Flow rate*. This is generally measured using a permanently fixed V-notch in the overflow channel. If the spring does not overflow then the *water level* in the pool is an alternative parameter that can be measured. In both cases corrections may be needed for leakage into the surrounding soil if the edges of the pool are not sealed.
2. *Chemistry* of the fluid emerging. Samples (approx. 250 ml) are collected from the overflow channel and taken to the laboratory for analysis of chloride content. Analyses of boron (B), magnesium (Mg), silica and sulphate (SO_4^-) may also be made and can prove useful.
3. *Temperature*. This is generally measured using a thermocouple, but it is important to take the measurement at the same point each time, especially if the spring discharges into a pool because local atmospheric conditions can affect the temperature near the water surface.

3.3 Thermal ground

Many natural thermal features lie within areas of thermal ground where the near surface (<1 m depth) ground temperatures are above ambient. Lateral variations in the temperature of thermal ground are often manifested by differences in vegetation species and the in the health (thermal stress) of individual species. Geothermal development may cause changes in the distribution and temperature of thermal ground, however, changes may have complex origins. It has been found that, in hot thermal ground, the near-surface temperatures are influenced more by groundwater depth than by groundwater temperature (Allis & Webber, 1984). This is thought to be due to the upward movement of steam and water vapour above a boiling or near-boiling groundwater surface (convection), which increases ground temperatures above that expected from a purely conductive temperature gradient. This effect, however, appears to be limited to about 10-20 m above the groundwater surface. If the boiling groundwater surface is deeper, then the near-surface temperatures are controlled more by thermal conduction. Thus, changes in the depth and temperature of the groundwater can affect the near-surface ground temperature.

Ground temperature can be monitored in several ways as seen below.

Thermal infra-red (TIR) imaging (Mongillo & Bromley, 1992)
Generally TIR imagery is obtained using a special camera mounted vertically in a low-flying (approx. 500m a.g.l.) helicopter or fixed–wing aircraft. An optical-mechanical scanning system in the camera focuses the TIR radiation emitted from the ground onto mercury-cadmium-telluride detectors, which give an electrical signal proportional to the intensity of radiation. The signals are recorded on standard

VHS video cassette for later analysis. The data are calibrated either internally (via an inbuilt reference) or externally (by measuring the temperature of identifiable water bodies during the survey). The survey is conducted on a grid pattern, with navigation by interactive GPS backed up by a visual record obtained from a vertically mounted video camera. To ensure that the effects of solar radiation are minimised, surveys are generally conducted after sunset. Such surveys require a high degree of skill and understanding by the operators to ensure that reliable data are obtained. After the survey, a large amount of computer processing of the data is needed to improve the information content in the images and to compile a TIR map. The equipment is capable of detecting temperature differences of about 0.2°C, but in practise differences of about 1-2°C are the best than can be determined between repeat surveys. The ground resolution depends on the height of the survey above ground surface, but generally a resolution of about 2x2 m is obtained. The results are often enhanced by pseudo-colouring and are easily incorporated into GIS archiving systems. Similar imagery can also be acquired by satellites but the present resolution of 15-30 m is not sufficient for monitoring purposes.

Problems: The main problems likely to be encountered are weather and ground conditions which may be unsuitable for long periods of time resulting in logistic and scheduling delays.

Advantages of this method are:
a) Complete coverage of a field or thermal areas can be acquired, thus quantitative determinations of areas of change can be obtained and changes to small-scale or inaccessible features can therefore be determined;
b) Information about the state of thermal stress to vegetation may also be obtained;
c) There is no need to obtain land occupier permission;
d) No ground based operations such as farming etc are disturbed.

Disadvantages of this method are:
a) Sophisticated and expensive equipment is required;
b) Highly skilled people are needed to perform the survey and for processing of the data;
c) Results cannot be obtained quickly because processing is required; thus unusual results cannot be easily checked.

Ground temperature measurements (Hunt & Bromley, 2000)
Shallow ground temperature measurements can be made quickly and cheaply at selected sites. The measurements must be made at 1 m depth, or greater, to minimise daily and seasonal temperature variations. In most cases the measurements will be confined to soil in the Vadose zone. The measurements are generally made with a thermocouple inserted in a wooden rod, connected to a hand-held display unit. A hole is first made in the ground with a steel rod or auger, and then the thermocouple rod inserted. Care is needed to ensure that the thermocouple is in good contact with the sides of the hole, and a few minutes taken for the measurements to stabilise. A survey may be in a grid pattern or at specific intervals along profile lines through the thermal ground.

Problems: The main problems likely to be encountered are:
a) Difficulty in exact reoccupation of the site measured in previous surveys due to vegetation growth, recent engineering works, or poor recording or marking of the site. Installation of a permanent marker helps to overcome this problem.
b) Large lateral changes in ground temperature due to steam heating. This is common in areas of high ground temperature (>50°C). In such cases it is desirable to make several measurements, about 1 m apart, at such sites to gauge the amount of lateral variation.
c) Variations due to seasonal ambient temperature changes. Surveys made in summer will generally result in greater measured temperatures than those made in winter. A correction for such effects can be obtained if the survey extends sufficiently far outside thermal ground and into ground having “normal” temperatures, thus providing a “base value” that can be used to put all repeat survey data on the same base.
d) Effects of rainfall. Heavy rainfall before a survey may quench the soil and cause a reduction in

the measured temperatures. To avoid this, surveys should not be made immediately after a period of heavy rainfall.

Advantages of this method are:
a) Low cost, especially where labour to cut paths through vegetation is cheap;
b) No sophisticated equipment is required;
c) Results can be obtained very quickly, even in the field during the survey;
d) Unusual results can be quickly checked.

Disadvantages of this method are:
a) The number and distribution of data points are limited;
b) In certain areas there may be danger to field staff from being burned or scalded;

4. MONITORING GROUND DEFORMATION

Experience has shown that both horizontal and vertical (subsidence, inflation) components of ground deformation (strain) occur together, although subsidence is the greatest. All data available indicate that exploitation-induced deformation is continuous in both space and time, i.e. there are no tares or asperities, except where tension cracks and compressional buckling occur at the ground surface. Generally each component is determined separately using different techniques.

4.1 Vertical deformation (Gabriel et al., 1989; Massonet et al., 1997)

Ground subsidence and inflation can be measured by repeat *levelling* using traditional optical survey techniques. Permanent survey marks (benchmarks) are installed in the ground or on permanent structures such as concrete pipeline supports. The elevation of these is then measured, relative to a base station outside the field, using standard 2nd or 3rd order techniques along closed loops. Temporary intermediate points are generally needed. In areas of high subsidence rate (>100 mm/yr) the levelling needs to be completed quickly to avoid introducing errors caused by ground movement between the start and closure of a loop. The frequency of surveys will depend on the rate of subsidence and the location of the subsidence area. At Wairakei field (New Zealand) the main steam lines are levelled every 6 months, the production area every 2 years, and the whole field about every 10 years.

Advantages of this method are:
a) Tradition technique, well known in all parts of the world;
b) Provides high-precision data if standard routines are correctly applied.

Disadvantages of this method are:
a) Slow (and hence expensive), especially in severe topography;
b) Information is restricted to survey lines;
c) Can be badly affected by atmospheric conditions in hot climates.

Vertical deformation can also be determined using *Synthetic Aperture Radar (SAR) Interferometry*. The technique involves interferometric comparison of radar imagery (commonly C-band with wavelength of 56.6 mm) obtained from satellites at different times. Imagery may be from the same or a different satellite, but if it is from a different satellite then more corrections and processing of the data are needed. Corrections for changes in atmospheric radar propagation delay are made, based on known or estimated variations in water vapour content of the troposphere. Corrections also need to be made for topography and are usually made from digital terrain data. Comparison of radar images taken at different times provides interferometric fringes corresponding to contours of equal change in satellite-to–ground distance. Each fringe corresponds to a change in distance of half a wavelength, which corresponds, to a vertical displacement of about 25 mm. Spatial resolution is typically 10 m. In practise, SAR interferometry is best when combined with some levelling profiles to provide ground truthing.

Advantages of this method are:
a) A complete map of displacement may be quickly obtained.

Disadvantages of this method are:
a) Precision is not as high as for levelling;
b) The method is not suited to high-rainfall areas with significant vegetation or forest;
c) Suitable imagery needs to be available for the area;
d) Sophisticated software and processing are needed, including digital terrain data.

4.2 Horizontal deformation

Horizontal deformation can be determined from repeat measurements of *horizontal angles* between reference points using a theodolite. Generally the reference points are permanent markers specifically installed for the purpose. At Ohaaki field (New Zealand), these consist of a concrete post made from a concrete drainage pipe (approx. 600 mm diameter), mounted vertically, set in a concrete pad and filled with concrete. A threaded pipe is set in the upper surface of the post to allow a theodolite, or a target, to be mounted on the post. Alternatively, a concrete pad can be installed with a brass or stainless steel pin to enable exact reoccupation of the site at future times. It is important that the reference points extend well outside the field. Standard first order triangulation survey techniques are then used to measure the angles between all visible reference points, and the network is connected to any national triangulation network. After a repeat survey (2-10 yr), the changes in angles are then used to compute the relative motions of the reference points. However, if a full determination of relative movements is to be obtained then observations of astronomical azimuths and distances between survey marks are required, in addition to angles. The main problems encountered with horizontal deformation surveys in New Zealand has been growth of vegetation and trees, necessitating the cutting of sight lines through forest which is expensive.

Advantages of this method are:
a) Equipment requires no batteries, and is more robust than elctromagnetic distance measuring equipment (EDM) (below);
b) Standard measurement techniques are used.

Disadvantages of this method are:
a) More time-consuming than use of EDM;
b) Precision not as high as for EDM

Horizontal deformation can also be determined from repeat measurements of *horizontal distances* between reference points using electromagnetic distance measuring equipment (EDM). Such equipment uses either laser light or microwave radiation. Similar reference points to those described above can be used, and both the transmitter/receiver and the reflectors are mounted on the threaded pipe. Surveys are best carried out at night to minimise the effects of differential expansion of the pillars by sunlight.

Advantages of this method are:
a) Quick;
b) Easy to use.

Disadvantages of this method are:
a) Equipment is not as easily portable as a theodolite;
b) Electronics are susceptible to breakdown requiring return to factory.

5. MONITORING GROUNDWATER CHANGES

5.1 Groundwater level (Driscoll,1986)

Variations in water level in the shallow unconfined groundwater aquifer can be easily measured in shallow monitor holes. These holes are about 3-5 cm diameter and generally drilled vertically using a small truck mounted auger. The depth of the hole depends on the depth of the water table, and needs to extend 5-10 m deeper than the natural water table. The hole should not be situated in a topographic hollow that might become flooded, close to roads, or within the grout screen area of a deep production well. The holes should be solid cased (PVC or similar) in the Vadose Zone, and slotted or screened casing used from the water table to the bottom. In places where the ground temperature is less than about 50°C then plastic (PVC or ABS) casing can be used, but for ground temperatures greater than this value steel casing should be used. The open area of the screened casing should approximate the natural porosity of the rock formation, and the slots should widen inwards to minimise plugging of the slots by fine formation material. A record should be kept of the casing pattern, and the position and elevation of the hole should be established by surveying. It is likely that over a long period of time, fine silt and debris will migrate through the screened casing and be deposited in the bottom of the hole. The casing should extend 10-20 cm above the ground surface and the top closed by a locking cap to prevent children dropping stones etc. into the hole or people using it as a water well. In fields with high gas content, there should be a small hole in the cap to allow escape of gas entering the well through the screened casing. The wellhead also needs to be indicated by a marker post and protected from damage by vehicles or animals. Where possible, the well should be at or close to a gravity monitoring benchmark.

Measurement of water level can be made using a simple electric circuit device powered by a small battery. Alternatively, a water level recorder can be installed which comprises a pressure transducer coupled to a data-logger set to record every hour.

5.2 Groundwater temperature

The temperature of groundwater can easily be measured in groundwater monitor holes using a digital thermometer and a probe. Where possible, the temperature should be measured not only at the water surface but also deeper in the monitor hole, to enable a temperature profile in the water to be obtained. The same equipment should be used for all measurements and the wires between the thermocouple sensor and the instrument should not contain any joints.

5.3 Groundwater chemistry (Ellis and Mahon, 1977; Glover and Stewart, 1996)

Samples for laboratory analysis are best obtained from groundwater monitor holes (above) after water level and temperature measurements have been made. Samples should not be taken from stale and stagnant water in these holes; only after 5-10 well-bore volumes of water have been removed and naturally replaced should a sample be collected. Removal of stagnant water and collection of the sample are generally done using a small portable electric pump.

Important parameters that should be measured are:
pH, chloride, lithium, sodium, potassium, magnesium, sulphate (SO_4), total silica (SiO_2), total bicarbonate (HCO_3) and fluoride. In addition, measurements of stable isotopes $\delta^{18}O$, $\delta^{2}H$, and tritium are worthwhile making.

6. MONITORING RESERVOIR MASS CHANGES

Generally developers routinely measure the amount of mass withdrawn from, and reinjected into the field. However, these measurements do not provide information about natural mass losses from thermal features or natural recharge. Changes in mass can be determined from microgravity monitoring at selected points. This method is described later.

7. MONITORING RESERVOIR CHEMISTRY CHANGES

Withdrawal of deep reservoir fluid generally induces recharge which may alter the chemistry of the alkali-chloride fluid, especially if a significant proportion of the recharge water has a very different chemistry. However, the situation may not be simple mixing because the recharge fluid may be one or more of the following:

a) Unmineralised, non-geothermal groundwater;
b) Acid-sulphate waters formed by condensation of geothermal gases in near surface oxygenated groundwater;
c) Bicarbonate waters formed by condensation of steam containing carbon dioxide and hydrogen sulphide in poorly-oxygenated, near-surface groundwater;
d) Seawater.

If the recharge fluid is unmineralised non-geothermal groundwater, or acid-sulphate water and bicarbonate waters that are low in chloride, then a reduction in chloride content of the reservoir liquid may occur in the discharge from wells in areas near where the invasion occurs. Monitoring of the dilution trends can provide information about the rate of lateral movement of the invasion front. However, if the field is adjacent to the ocean and seawater is drawn in (such as at Tiwi field, Philippines) then the chloride concentration may increase. From a suite of chemical species it is generally possible, using a mixing diagram, to determine the amount of mixing of the various components.

Samples can easily be obtained for analysis by sampling the weir box associated with a wellhead separator, sampling a 2-phase pipeline from the well, sampling from a weir box, or using a downhole sampler. Details about sampling procedure, corrections needed, and analysis techniques are given in standard textbooks (Ellis & Mahon, 1977; Henley et al., 1984; Nicholson, 1993).

8. MONITORING CLIMATIC CONDITIONS

In order to assess the influence of variations in climatic conditions on thermal features, and groundwater temperatures and levels it is necessary to also measure rainfall, air temperature and air pressure. These can generally be obtained from a weather observatory installed near the power station. In the early stages of development it is generally necessary to install several small weather observatories, in and around the geothermal field, to collect information which will enable various air discharge scenarios for the power station to be modelled.

9. INTERPRETATION OF MONITORING DATA

Generally, the process of collecting monitoring data is relatively straightforward. However, correct interpretation of the results may be difficult. Often the first problem in interpretation is separating natural variations from those induced by exploitation of the field. Further complexities may be introduced by other human activities. For example, the removal of trees, pumping of water supply wells, and diversion or damming of rivers in and near the field may cause groundwater level changes. The effects of these may be difficult to measure or even estimate. Monitoring results are often field or region-specific. For example, in New Zealand geothermal fields the natural ground water level changes have a seasonal variation of about $\pm$1 m, but in some geothermal fields in Japan the variation is 10 m. Furthermore, each set of monitoring results needs to be interpreted in relation to other results. For example, changes in ground temperature need to be analysed together with changes in groundwater level and groundwater temperature.

10. USE OF MONITORING RESULTS

10.1 Review panel

The monitoring data and interpretations need to be actively used, and not merely filed away. A common problem is that regulatory authorities rarely (at least in NZ) have scientific or engineering staff with the appropriate qualifications and experience to assess the monitoring data. To overcome this problem in New Zealand, the monitoring results are initially examined by a Review Panel. Each developed field has a separate Panel. The panels are composed of 3 geothermal experts who are independent of the developer, and often contain retired geothermal professionals and university staff. The panels meet twice yearly for the first two years of development, then annually after that, to examine the results of the monitoring programme which are prepared by the developer and given to panel members prior to the panel meetings. The formal meetings last about one day, and the costs are paid by the developer. The Panel then prepares a report to the regulatory authority, which may then recommend changes to the way in which the development proceeds and any further monitoring that might be needed. Data and interpretations provided by the developer to the panel, and the panel reports are considered to be public information and can be requested by any member of the public, except that the developer may request that certain information which might be of commercial value be kept secret.

10.2 Permitting

In New Zealand, all geothermal developers must apply every 10-20 years to the regulatory authority for their permits (Resource Consents) to be renewed. The permitting process in New Zealand will be described later.

10.3 Common failures in monitoring

Experience has shown that few monitoring programmes are adequately planned and executed. Regulatory authorities must beware that this may be a deliberate policy or subconscious action of developers in order to obscure or make worthless any embarrassing data while still appearing to comply with the regulations. Common problems are:

- Failure to start measurements well before production begins, so that a good baseline is not obtained;
- Failure to extend measurements, particularly ground deformation and microgravity, outside the field, resulting in poor or ambiguous results;
- Failure to make measurements at a sufficient number of points to ensure that the inevitable loss of some points does not cripple the monitoring programme;
- Failure to use trained staff, resulting in poor data being obtained and leading to doubt that true comparisons can be made;
- Failure to adequately document the monitoring data;
- Failure by regulatory authorities to check that monitoring is being carried out when required and

to the specified precision.

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GEOTHERMAL TRAINING PROGRAMME

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LECTURE 4

PROTECTING THE ENVIRONMENT

1. PROTECTION THROUGH MANAGEMENT PRACTISES

Prime responsibility for protecting the environment during a geothermal development rests with the developer, and specifically with the engineers and managers of the project. This responsibility cannot be shifted to the scientists, the regulatory authorities, the company shareholders, the government, or the workers.

Some general principles for protecting the environment are:

- *Monitor the environment.* Having good information is essential to enable problems to be identified and corrective action taken before they become serious and irreversible.
- *Rely on scientists to recognise the problems, but not to remedy them.* The training in their discipline often heavily influences the judgement of specialist scientists, but important decisions involving the environment requires understanding of many disciplines.
- *Act before scientific consensus is achieved.* Scientists rarely agree that something is absolutely certain. Calls for additional research may be delaying tactics or made to extend funding.
- *Confront uncertainty.* Do not believe that science or technology can provide a solution to every environmental problem. Effective management policies are possible under conditions of uncertainty, but they must take uncertainty into account. Favour actions that are robust to uncertainty and are reversible.
- *Include human motivation.* Short-sightedness and greed are often responsible for environmental problems, and this should be recognised in management practises. Resist pressure for short-term gains at the risk of environmental problems.
- *Take a precautionary approach.* Do not take actions for which there is doubt about the environmental outcome.
- *Be prepared for worst case scenarios.*

2. PROTECTION THROUGH ENGINEERING PRACTISES

2.1 Minimising impact of access and field development

Destruction of forests and vegetation resulting from construction of road access to drilling sites can be minimised by *careful planning* to reduce the number of steeply-sloping exposed banks. Remedial action can be taken to reduce erosion such as *planting fast-growing trees* which bind the soil, and *planting grass, crops, or low vegetation* beneath and alongside pipeline routes to increase surface run-off and minimise scouring of unprotected soil (Hunt and Brown, 1996). It is also important to consult with local people to ensure that places of cultural importance are not damaged or destroyed.

2.2 Reducing the effects of drilling operations

Noise inevitably occurs during the exploration drilling, construction and production phases of development. Air drilling is the most noisy (120 dBA) due to the "blow pipe" where the gases exit. *Suitable muffling* can reduce this to around 85 dBA (Brown, 1995). Mud drilling is quieter at around 80 dBA. Diesel engines operating the compressor and electricity supplies can also produce a resonant sound that carries for long distances; this noise can be constrained, to less than 55 dBA during the day and 45 dBA at night, by *suitable muffling* and *constraining noisy operations* (such as tripping or cementing) *to* *the daytime hours.* *Construction of screens of sound-absorbing material*, such as vegetation, can also reduce the impacts of drilling noise.

Following drilling, a well is usually discharged to remove drilling debris. Such vertical discharges are very noisy (up to 120 dBA). After this, there is normally a period of well testing; this can be suitably muffled by the *use of silencers,* but even then the noise is still significant (70-110 dBA). The well is then put on "bleed" where the noise is around 85 dBA reduced to 65 dBA if the "bleed" is led to a rock muffler (Brown, 1995).

The effects of using powerful lamps to light the work site at night may be reduced by *temporary screens and careful placement of the lamps.*

To reduce noise associated with the use of heavy machinery there must be *suitable muffling on the exhausts of the earth moving equipment.*

2.3 Disposal of waste drilling fluid

Discharge of waste fluids into nearby waterways is no longer acceptable. Modern drilling techniques involve *using minimal amounts of fluid and recycling* as much as possible.

2.4 Reducing possibility of degradation of thermal features

The decline in thermal features is associated with the decline in reservoir pressure. The only way to prevent or minimise the decline of thermal features is therefore to *minimise reduction in reservoir pressures* (Hunt and Brown, 1996). At present there are no viable techniques available to do this without severely curtailing production. The only possible technique would be to alter the way in which the energy is used, such as by not removing the fluid but instead only mining the heat using heat exchangers. However, with current technology, this would involve a large reduction in the amount of energy that could be extracted, and necessitate drilling more wells.

2.5 Avoiding depletion of groundwater

If exploitation of the system results in a large pressure drop in the reservoir, the groundwater may be drawn down into the reservoir along high-permeability paths. If the lateral permeability of the rocks in the groundwater zone is low then the downflow may result in a drop in the groundwater level. Downflows may also occur as a result of breaks in the casing of disused wells, and cause groundwater level changes.

The best ways of preventing changes in groundwater level are to *maintain reservoir pressure,* and *promptly repair damaged wells* (Hunt and Brown, 1996).

2.6 Changes in ground temperature

The only way to prevent increased heat flows is to minimise the extent of the 2-phase zone by *maintaining reservoir pressures* (Hunt and Brown, 1996). However, experience suggests the areas of high heat flow and ground temperatures are usually localised and do not cause significant environmental problems.

2.7 Ground deformation

Ground movements have been recorded in most high-temperature geothermal fields in New Zealand, at Cerro Prieto (Mexico), Larderello (Italy), and The Geysers (USA), and have led to:

a) Compressional and tensional strain on pipelines and lined canals;
b) Deformation of drill casing;
c) Tilting of buildings and the equipment inside;
d) Breaking of road surfaces;
e) Alteration of the gradient of streams and rivers.

Little can be done to prevent the effects of ground deformation, except to *maintain reservoir pressure*. Experience suggests that subsidence is difficult to reverse by increasing reservoir pressure because of the great weight of rock overlying the formation that has compacted. The effects of deformation on pipelines can be reduced by *mounting the pipelines on rollers*, but experience at Wairakei shows that even with such assistance sections of pipe need periodically to be removed or installed to maintain the pipeline network. Equipment that is sensitive to level should be *mounted on an adjustable base.*

2.8 Hydrothermal eruptions

Hydrothermal eruptions cannot at present be reliably predicted, however three separate causes have been identified to increase the likelihood of an eruption (Bromley and Mongillo, 1994). The first mechanism assumes an expanding 2-phase zone in the reservoir due to exploitation which increases steam flow to the surface. Near the surface, aquicludes may restrict the flow of steam and pressures can increase. During long dry periods, the thickness of the near-surface aquifer is reduced and further increased heating and steam flow occurs. If a period of heavy rainfall then occurs, the permeability of the ground is reduced so that the steam cannot escape and pressures can be further increased to the point where an eruption happens. The second mechanism involves hydraulic fracturing allowing a release of non-condensable gases to decrease the boiling point close to the surface. The third mechanism is a reduction in the lithostatic pressure by removal of the overburden, either naturally by landslides or by man-made excavations.

There are no countermeasures available apart from *maintaining reservoir pressures* to minimise steam formation and the concomitant increase in heat flow, and *refrain from building on or excavating in active thermal ground.*

2.9 Mitigating the effects of waste liquid disposal on living organisms

Release of hot waste water from power station directly into an existing natural waterway, may increase the temperature sufficiently to kill fish and plants near the outlet. Temperatures can be reduced by cooling the waste water prior to release using either forced- or natural-draft cooling towers, or natural cooling in open ponds. Alternatively, the heat can be used to generate more power by using a binary-cycle plant, and then "cascaded" further, through heat exchangers, for use in industrial or agricultural processes.

Release of untreated waste into a waterway can result in chemical poisoning of fish, and also birds and animals which reside near the water because some of the toxic substances move up the "food chain". Some effluent treatment processes exist to remove minerals from the waste water, but these are generally uneconomic, although research is currently underway in this area to develop more commercially feasible solutions where minerals are extracted for use in industrial processes (e.g. silica for whitening paper). Ponding, (which reduces the temperature of water and encourages the minerals to precipitate and sediment out) can assist.

The best way of mitigating the impacts of waste water disposal is to ensure that all waste water and condensate are collected and *reinjected in deep wells* at the edge of the field.

2.10 Avoiding effects of waste liquid contaminating groundwater

Release of waste water into cooling ponds or waterways may result in shallow groundwater supplies becoming contaminated and unfit for human use. Also, ponding may lead to contamination of groundwater if the pond lining is not impermeable or becomes accidentally broken. The best means of avoiding this is to *reinject all waste liquid.*

2.11 Minimising induced seismicity

Reinjection may cause an increase in the number of small magnitude earthquakes (microearthquakes) within the field. The increase is caused by high wellhead reinjection pressures increase the pore pressure at depth, particularly in existing fractures, which allows movement to suddenly release the stress and resulting in an earthquake.

The only effective countermeasures are to *reduce reinjection pressures to a minimum, and to ensure that all structures in the field are earthquake resistant.*

2.12 Minimising the effects waste gas disposal on living organisms

Standard countermeasures are based on minimising the release of gases into the atmosphere by *reinjecting all waste fluids, designing power stations to minimise gas discharges,* and *employing active monitoring systems* to enable the power plants to be shut down or generation reduced if the amounts of gas discharged exceed set levels. Hydrogen sulfide emissions can be reduced using a variety of techniques. Once the gases have been discharged there are no ways in which they can be controlled.

2.13 Reducing microclimatic effects

Even in geothermal power schemes which have complete reinjection, a considerable amount of gas (mainly steam) may be lost to the atmosphere. For example, at Ohaaki, of 70 Mt of fluid withdrawn (1988 - 1993) about 20 Mt (nearly 30%) was discharged to the atmosphere. Such discharges of warm water vapour may have a significant effect on the climate in the vicinity of the power station, depending on the topography, rainfall, and wind patterns. Under certain conditions there may be increased fog, cloud or rainfall. Microclimatic effects are mainly confined to large power schemes on high-temperature fields; exploitation of low-temperature geothermal systems does not cause significant microclimatic effects.

Countermeasures include *adequate investigation and planning of the power scheme before construction, design of the power station to minimise discharges***,** and *active monitoring and control of discharges* when the plant is in operation.

3. PROTECTION THROUGH REGULATIONS

Although the adverse effects of geothermal development can be avoided or minimised through the methods described above, it is generally recognised that geothermal developments need to be controlled and monitored by independent regulatory authorities through enforceable regulations. Experience in other natural resource operations suggests, regrettably, that if a developer is allowed unfettered access to a resource the environment often suffers. In most countries these authorities are central, regional or local government, and they issue (to developers) permits or consents which ensure that the best environmental practises are followed (Hietter, 1995; Goff, 2000). This is not entirely altruistic because if severe environmental damage occurs it is generally government that has to take ultimate responsibility for the problem. The permitting process varies from country to country, but generally involves:

a) Preparation of an Environmental Impact Report (EIR);
b) Consideration of that report by officials, experts and the public;
c) Granting of permits subject to restrictions;
d) Setting up of a monitoring programme and measurements taken regularly;
e) Periodic review of the monitoring data and renewal of the permits.

Some countries also require that a geothermal development be "sustainable", and this often leads to semantic arguments.

3.1 Permitting in New Zealand

New Zealand has several Acts of Parliament that work together to regulate and guide environmental use in a sustainable and integrated way. These acts work in accordance with the internationally accepted principles of Integrated Resource Management, which seeks to ensure that international environmental goals are achieved through locally appropriate practices with the agreement and participation of local communities and other stake-holders. Management of much of this process is devolved from central government to regional and to local government (Luketina, 2000).

The principal act which affects geothermal developments is the *Resource Management Act* 1991 (*RMA*) which sets out how people are to use air, land, and water (including geothermal fluid). Others include the Hazardous Substances and New Organisms Act and the Biosecurity Act. The RMA devolves management of these resources to regional councils (regional government).

The RMA sets out restrictions on the use of geothermal water and heat. No person may take, use, dam, or divert water or geothermal heat unless allowed by a rule in a *regional plan*, or by a *resource consent* issued by the relevant regional council, or unless the activity is for reasonable domestic use or for communal traditional use by the local Maori (the indigenous people of New Zealand).

Other sections that are relevant to geothermal use place restrictions on the discharge of contaminants to the environment, and on land uses such as drilling.

The RMA separates resource use activities into several classes:
1) *Permitted activity* is a small-scale activity with minimal potential for adverse environmental effects. It is allowed by a regional plan without a resource consent if it complies with certain conditions set down in the regional plan.
2) *Controlled activity* requires a resource consent, and has minor potential for adverse environmental effects. The resource consent will be granted if the activity meets certain conditions set down in the regional plan. The application for the consent is unlikely to be notified for public submission, and is generally decided by council staff.
3) *Discretionary activity* is a large-scale activity requiring a resource consent. The application will likely be publicly notified. If submissions against it are received, it will be decided by councillors after a public hearing.
4) *Non-complying activity* means an activity which contravenes a rule in a plan and requires a resource consent. The application will likely be publicly notified.
5) *Prohibited activity* means an activity which the regional plan expressly prohibits and for which no resource consent shall be granted.

Regional plans and policy statements: The RMA requires each regional council to put in place a regional policy statement and a regional plan. The regional policy statement sets the policy, "by providing an overview of the resource management issues of the region and policies and methods to achieve integrated management of the natural and physical resources of the whole region". The regional plan provides the rules to implement the policy and to "assist a regional council to carry out any of its functions in order to achieve the purpose of this act".

There is a set procedure for developing the policy statement or plan:
1) Preparation;
2) Consultation;
3) Public notification of proposed policy statement or plan;
4) Submissions;
5) Public notification of submissions;
6) Further submissions;
7) Hearing by the regional council;
8) Notification of regional council's decision;
9) Reference (submissions) to the *environment court;*
10) Environment court hearing;
11) Amendment of the proposed policy statement or plan;
12) Approval;
13) Policy statement or plan made operative.

3.2 Waikato regional council regional policy statement

The geothermal section of the Waikato regional council's regional policy statement identifies the major geothermal management issues as being the following:

1) Maintaining the variety of characteristics of the regional geothermal resource; and
2) Ensuring efficient take and use of the geothermal resource.

For geothermal resources there are several considerations in terms of sustainable management which form the Waikato regional council policies.

Sustainable production: Ensuring that users, such as large geothermal power developments, do not take geothermal fluid from the earth faster than it can be replaced.

Biodiversity: Ensuring that the biodiversity of geothermal micro-organisms, plants and animals is maintained for its own intrinsic value and for possible use in industrial processes and medical applications.

Preservation of features: Ensuring that geothermal features that people value for their cultural, amenity, and scientific values such as geysers, mud pools, and silica terraces are maintained for future generations to enjoy and learn from.

Efficient use: Ensuring that when geothermal resources are used, they are used efficiently.

Maori values: Ensuring that Maori traditional values are recognised and provided for.

3.3 Waikato regional council regional plan

The regional plan sets out the rules for achieving the aims and objectives of the regional policy statement. In the geothermal chapter of this plan there are several broad concepts from which the rules derive:

Classification of systems: The geothermal systems of the region are classified into development, protected, or unclassified systems. System boundaries are defined according to electrical resistivity contours and other survey information. Classifications and boundaries can be changed through a formal process by providing sufficient evidence that a change is warranted.

Protected systems: Takes and discharges of geothermal water from and to land (other than those lawfully established prior to notification of the plan) on protected systems will be prohibited.

Unclassified systems: New takes and discharges from unclassified systems will be a discretionary activity. Existing uses lawfully established prior to notification of the plan will be a permitted activity in unclassified systems.

Development systems: The take from and discharge to land of less than 30 t/d of geothermal fluid will be permitted (under certain conditions). Other takes and discharges up to 500 t/d will be discretionary or controlled activities. The take and discharge of more than 500 t/d will be a discretionary activity.

Significant geothermal features: The regional plan contains a list of significant geothermal features in the region, ranked in order of importance based on rarity, resilience, and viability. They are found on many of the geothermal systems mentioned above, including development systems. Resource consents are needed to do anything in or around a significant geothermal feature.

3.4 The resource consent process

Assessment of environmental effects: According to rules set down in the RMA, a resource consent application must be accompanied by an assessment of any actual or potential effects that the activity may have on the environment and the ways in which any adverse effect on the environment may be mitigated.

Consultation: An application for a resource consent must include evidence that all reasonable steps have been taken by the applicant to engage in adequate consultation with interested parties. These parties may include adjacent landowners and occupiers of land, local iwi (native tribes), the Department of Conservation, the relevant district council, environmental groups and special interest groups such as fishing and hunting clubs.

Notification: A resource consent application must be publicly notified, and served on such persons who are likely to be directly affected by the application. This is done by placing advertisements in papers and sending letters to affected and interested parties. Notification is not required if all affected parties provide their approval.

Submissions: Submissions can be made in support, in opposition, or neutral to the application. If anyone submits in opposition to the application, the application and submissions have to be heard in a formal hearing process by a hearings committee.

Prehearing meetings: Prehearing meetings can be held between the applicant and submitters in order to address the concerns of the submitters. They can range from a brief meeting between the parties to a formal public meeting with an independent facilitator or chairman.

The decision: If there were no submissions against the application, the decision is made by council staff. If there were submissions against the application a hearing is held. The hearing committee is usually made up of three elected council members. At the hearing, the applicant, the submitters, and council staff present evidence, as if in a law court. Then the committee make their decision based on the evidence, stating whether the consents are to be granted, their duration, and what the conditions are.

Appeals: If the applicant does not agree with the decision made by council staff, they may appeal to the council. In the case of a decision made by hearings committee, the applicant or any of the submitters may appeal to the environment court. The environment court is presided over by a judge and operates in the manner of a full judicial court. Applicants to the court need lawyers, and the winner may have to pay all the costs of the loser. A decision of the environment court may be appealed in the High Court, but only on a question of law.

Costs: The costs associated with obtaining a Resource Consent depend on several factors such as
- How detailed the applicant's Assessment of Environmental Effects needs to be;
- How long Council staff spend assessing the application;
- Whether the application needs to be notified;
- Whether there are submitters against the application, which leads to a hearing;
- Whether the consent decision is appealed in the Environment Court.

3.5 Resource consent conditions

Resource consent conditions fall into three main types:

- *Physical conditions* limiting the physical details of what the consent allows, e.g. volume of take or discharge, location of take or discharge;
- *Monitoring conditions* requiring environmental monitoring and reporting;
- *Standard conditions* relating to such administrative matters as site access, opportunity to review conditions, and consent-holder charges.

Recently Waikato regional council has adopted a policy of requiring developers wishing to drill a deep geothermal well to provide a $200,000 bond to cover "abandonment" costs in the event of the company being unable or unwilling to close in the bore at the end of its useful life. Closure must be to the standards of the Code of practice for deep geothermal wells.

All consents except the bore permits carry an annual charge. The charge is in the range US$30-1000. Most geothermal power stations have about 15 consents costing about US$700 each, per annum, to cover administration, general environmental information gathering, state of the environment reporting, and development of policy and plans.

The RMA requires regional councils to monitor consents. Each year in the Waikato region, theconsents for geothermal developments are examined to see whether monitoring and reporting conditions have been complied with. The site is visited by council staff, who also look for unauthorised activities and potential hazards. Compliance monitoring reports are then sent to the developer setting out the consent conditions which have not been complied with (if any), and any issues of concern to council staff.

From time to time people make complaints regarding various activities of geothermal power stations. Examples include discharging pollutants to a river, dumping asbestos into geothermal features, discharging to air without a consent, H_2S odour nuisance, steam nuisance across a road, taking more steam than their consent allows, and diverting a stream without a consent. All complaints are investigated. A staff member will usually go to the site and take samples, photos, and other evidence where appropriate, interview people on site, and interview the complainant. If the complaint is justified, prosecution may ensue but usually it is enough to threaten to prosecute. Regional councils are able to recover all costs for a justifiable complaint.

If a developer contravenes a regulation or resource consent, the council can issue a legally enforceable *abatement notice* ordering them to stop. The developer can appeal to the environment court against the abatement notice. If they do so, they can continue with the activity until the case is heard. In order to make sure that the person has no right of appeal, the council can apply to the environment court for an *enforcement order*. This takes effect once the case is heard. To make sure that the person stops the activity immediately the council can apply to the district court or the environment court for *an interim enforcement order*. If granted, this will remain in force until the *enforcement order* is heard, or until it is cancelled.

A developer can be prosecuted for contravening those sections of the RMA which impose duties and restrictions in relation to land, subdivision, the coastal marine area, the beds of certain rivers and lakes, water, and discharges of contaminants, any enforcement order or abatement notice, and a range of other provisions. Penalties include imprisonment for up to 2 years and fines of up to US$100,000 plus a further fine of up to US$5,000 for every day that the offence continues.

Some regional councils have set up a *review panel* for each development, consisting of 3-5 geothermal experts (scientists and engineers)who are independent of the developer, to advise council about the development. Each year the developer has to submit a report about its operations to the panel, which then considers the report and gives its opinion to council about the state of the resource and makes suggestions about how the developer could improve the use of the resource and protection of the environment. The review panel may meet for 1-3 days each year, and the cost of the panel is borne by the developer. The use of a review panel minimises the need for council to have experts on its staff.

3.6 Case study: Consents for Ohaaki power station

In 1997 Contact Energy Ltd started liasing with Environment Waikato regarding renewal of resource consents for the Ohaaki geothermal power station. Several meetings were held and in late 1997 a draft application was presented to Waikato Regional Council for comment. In the meantime, Contact Energy Ltd were preparing their technical appendices and engaging in consultation meetings with affected parties including the local Maori tribe (on whose land the station was built by the government) and other local landowners.

A formal application was received from Contact Energy Limited in April 1998 for 15 resource consents to:

- Take and use up to 60,000 t/d of geothermal water;
- Take and use up to 71,000 t/d of water from the Waikato River for cooling ;
- Divert stormwater and to take and/or divert groundwater;
- Discharge up to 54,000 t/d of separated geothermal water via reinjection wells;
- Discharge stormwater onto and into land;
- Discharge up to 147,000 t/d of stormwater to the Waikato River;
- Discharge up to 2,000 t/d of geothermal water to the Waikato River;
- For the discharge of cooling water onto or into land) in the event of an emergency;
- Discharge antiscalants into land via wells (including circumstances where they may enter water);
- Discharge sewage into land and underground water through septic tanks;
- Discharge up to 2,400 t/d of separated geothermal water to the Ohaaki Pool;
- Discharge geothermal water from the Ohaaki Pool to the Waikato River;
- Discharge debris to the Waikato River associated with the cleaning of the water intake screens;
- Construct and upgrade structures in, on, under, and/or over the bed of the Waikato River;
- Excavation, well drilling, metal extraction, earthworks, roadwork's, less than 5 metres from the bed of the Waikato River.

The application requested a term of 25 years. The application was a 150-page document accompanied by a set of technical appendices of several hundred pages.

The application was publicly notified in local newspapers, and nine submissions were received. Six were in opposition, one was neutral, and two were in support subject to conditions of consent. Land subsidence was a major issue for the local Maori people whose sacred sites and buildings were subsiding into the Waikato River.

A *hearings committee* comprising of councillors conducted a four-day hearing for the purpose of enquiring into the application and submissions thereto. A site visit was held as part of the hearing, including a visit to sites of spiritual significance to local Maori.

The *hearing* was adjourned in September 1998 for a period of four weeks following a request from a submitter for the committee to seek legal advice regarding whether the committee was able to call an adjournment for a year in order to give the applicant time to satisfy the concerns of the submitter.

The hearing was closed in October 1998. The committee had received legal advice that an adjournment of one year was not allowed for in the RMA. The committee recommended that the application be granted and that a term of 15 years be applied as:

- Predictions beyond 15 years are difficult to provide with accuracy;
- Significant effects have occurred over a period of 10 years;
- Most submitters had relevant concerns about a longer term including effects, changes in technology, economic stability, and site management of owners, new or otherwise.

In November 1998 a landowner of part of the Ohaaki land appealed to the environment court against the decision, on the grounds that the decision would result in further land subsidence. On the same day Contact Energy Ltd filed an appeal against the decision on the grounds that the term should be for 25 years. Contact Energy also applied to the court to have the appeal struck out on the grounds that the person had not himself submitted to the application, and therefore had no status before the court.

The landowners appeal was subsequently struck out by the judge, who found that the person was not a beneficial landowner, although his father was. Contact Energy's appeal against the term was then withdrawn and the consents granted.

3.7 Results of the RMA process

The public hearing process has generally worked well for members of the public because they have the opportunity to directly voice their environmental concerns to the regulatory authorities in an informal setting. Furthermore, information about a development and the results of monitoring becomes public knowledge.

However, the developer has more financial resources than individual members of the public and if the resource consents are not obtained, or obtained with what the developer considers are onerous conditions, then an appeal is often made to the environment court. Defending such an appeal may be very costly, and few individuals can risk losing such a case. The cost and publicity of legal action also can intimidate councils.

An unexpected outcome of the RMA process has been its use by one developer to stop or hinder a competitor. Each developer opposes granting of resource consents to competitors on environmental grounds. Since they both have the financial resources to hire lawyers and scientists to argue their respective cases, the hearings and court cases become extended. An additional, and unfortunate, outcome of this has been that developers have concentrated on the legal battles to the detriment of other activities that might improve the environment, and have reduced monitoring to the minimum required because it may be used in evidence against them.

4. PROTECTION THROUGH ECONOMIC MEASURES

4.1 Royalty or user charges

Rotorua provides a good example of how economic measures can be used to protect the environment, and how these may in some circumstances be superior to regulations (O'Shaughnessy, 2000).

The Rotorua City Geothermal Empowering Act 1967 (RCGEA) gave the Rotorua district council (local government) control of all geothermal use within the city. However, despite the requirement by this act to issue licences, no licences were issued during the 19 years the act was in force. This was, in part, because the act focussed on safe exploitation of geothermal energy, with no regard for sustainability of the resource or protection of surface thermal features. In 1979, when Papakura Geyser ceased erupting, public and scientific concern resulted in the Rotorua district council imposing a moratorium (in 1980) on any new wells being drilled (Figure 33) within a 1.5 km radius of Pohutu Geyser. However, replacement of existing wells was allowed in this zone, with often farcical consequences. For example, a property with a house would be bought by a company and re-developed as a motel complex, the small shallow well on the property was then alleged to have "failed", and replaced by a deeper and larger diameter well from which a much greater quantity of hot water and steam was drawn. Extraction of geothermal water within 1.5 km of Pohutu Geyser was therefore allowed to increase significantly under that policy. This lack of effective management contributed to central government revoking the RCGEA in 1986, and forcing the closure of all wells within 1.5 km of Pohutu Geyser. The district council may secretly have welcomed this intervention by central government, because it removed from them any need to enforce locally unpopular management conditions.

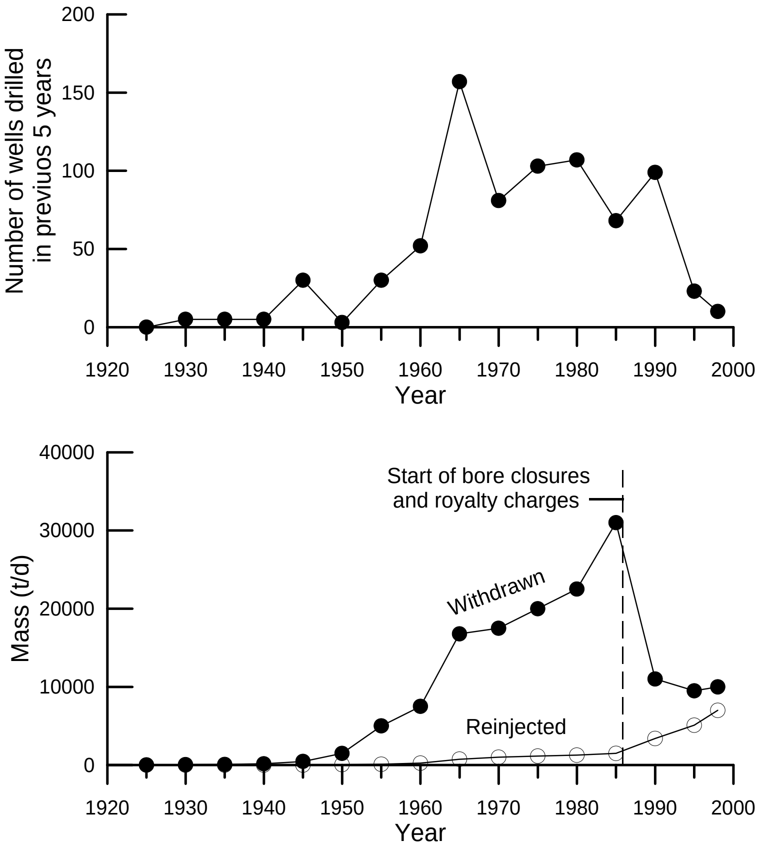

FIGURE 33: Graphs showing the number of new wells drilled and mass of fluid withdrawn and reinjected at Rotorua City; note the decrease in number of new wells drilled and increase in the amount of fluid reinjected following imposition of economic measures

A punitive annual royalty charge was also imposed on all remaining wells, starting from 1 April 1987. These were deliberately set at a high level and were calculated on the maximum possible well discharge and temperature, regardless of actual use. Depending on which part of the city a well was located, this led to many anomalies; i.e. a single pensioner could have incurred royalty fees of US$7,000 per year, whereas a large motel with a low-pressure/low-temperature well might have paid only US$300 per year. However, these royalty charges were very efficient in further reducing total well draw-off during 1987-1992. At the start of this period, many people took advantage of an opportunity for free closure by cement grouting to escape the annual royalty charges. This resulted in a greater reduction of well draw-off (approximately 125 wells closed) than did the enforced closures of wells.

4.2 Bonds

Another economic measure which can be effectively used to protect the environment is the requirement for a developer to deposit a large refundable bond that is forfeited if environmental damage occurs. Interest on the bond money, less an amount to cover taxes and inflation, would be returned annually to the developer. Although the damage may not be able to be rectified by money, the potential loss of a large amount of money may keep a developer more focussed on the environment and the consequences of his actions. Such a system is particularly effective when there is the suspicion that a development company will not be able to meet its obligations either through lack of expertise or financial problems. Another situation where this is effective is for a public company where the profits, share value, and bonuses of the managers may be adversely affected by loss of the bond.

5. SUMMARY

Effective countermeasures are available to minimise most impacts. These include:

- Careful planning to reduce impacts of access and site development;
- Muffling of equipment to reduce drilling and operational noise;
- Maintaining reservoir pressures to lessen the chances of natural thermal features and groundwater supplies being affected, and ground subsidence occurring;
- Reinjecting all waste liquids deep into the ground to avoid potentially toxic fluids affecting living organisms and contaminating shallow groundwater aquifers;
- Minimising reinjection pressures to reduce the chances of inducing small earthquakes;
- Designing power stations to minimise gas discharges.

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Reports 2000
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LECTURE 5

MICROGRAVITY MONITORING

1. GRAVITY

1.1 Fundamental concepts

Gravity is a fundamental, attractive, force *(f)* which acts between all bodies of matter, and is given by Newton's Universal Law of Gravitation.

$$f = -G\left(\frac{M_1 M_2}{r^2}\right)$$

where G is the universal gravitational constant (6.673 x 10^{-11} m^3 kg^{-1} s^{-2}), M_1 and M_2 are the masses of the bodies, and r is the distance between them. Rearranging this equation

$$f = M_1\left(\frac{-GM_2}{r^2}\right) = M_1 g_2$$

Newton's 2nd Law of Motion states that force is the product of mass and acceleration, hence g_2 represents an acceleration. If M_1 is free to move, it will be drawn towards M_2 at a speed which constantly increases (accelerates) at a rate g_2. The term g_2 is the value of gravity of M_2 at distance r, thus *gravity is the capacity of a body to accelerate other objects*. In practice, for geophysicists, it is the force which causes unsupported objects near the Earth's surface to move towards the centre of the Earth.

The force of gravity exerted by a body is pervasive and acts on all other bodies in the universe. It is a potential field, and has no gaps or discontinuities. The force of gravity at a point can be represented by a vector whose magnitude and direction are the sum of the attraction of all bodies in the universe. In practice, however, the main component of gravity at points on the Earth's surface is from the Earth itself (99.9999%), with secondary components from the Sun and Moon. The gravity effects (at the Earth's surface) of other celestial bodies (planets, stars) are negligible, despite what astrologers might say.

1.2 Units

A gravitational field may be characterised in two equivalent ways: by the acceleration produced on a body placed in the field or by the force produced per unit mass. These lead, in the S.I. (System International) to the dimensionally equivalent units of metre per second squared (m/s^2) and Newton per kilogram (N/kg) respectively. However, a common unit of gravity used in geophysics is the *gal* (named after the astronomer Gallileo), and derived from the old cgs system of units:1 gal = 1 cm/s^2 = 10^{-2} m/s^2. In microgravity work this unit is too large and a sub-multiple, the *microgal*, is generally used:

$$1 \text{ microgal } (\mu\text{gal}) = 10^{-8} \text{ m/s}^2$$

The term *microgravity* is generally used to distinguish data in the range 1-500 microgal (0.001-0.5 milligal) from those in geophysical prospecting (Bouguer anomalies) which usually lie in the range 500-100,000 microgal (0.5-100 milligal). Microgravity measurements are therefore 1- 2 orders of magnitude smaller than those normally encountered in geophysical prospecting. Values of gravity on the Earth's surface are about 9.8 m/s^2 (9.8 x 10^8 microgal), hence one microgal represents about 1 part in 1000 million of the Earth's field.

2. EARTH'S GRAVITY FIELD

2.1 Components of the gravity field

Gravity at points on the Earth's surface has two principal components:

a) *Mass component* - caused by the direct attraction of the mass of the Earth itself (including its atmosphere) and of the Sun and Moon. This is oriented inwards towards the centre of the Earth:

$$f_m = \frac{GM}{r^2}$$

where G = Universal gravitational constant;
M = Mass of the Earth; and
r = Distance of the point from the centre of mass.

b) *Centrifugal component* - that caused by the effects of the diurnal (daily) rotation of the Earth. This is oriented perpendicular to the axis of rotation (line joining the geographical poles) and is outwards:

$$f_c = w^2 d$$

where w = Angular velocity of rotation; and
d = Distance from the axis of rotation.

The value of gravity at a point on the Earth's surface is the vector sum of these two components, however, the mass component is much larger than the centrifugal component.

2.2 Variation with position

Because of the Earth's rotation and finite rigidity the Earth is not a perfect sphere but an ellipsoid, and so the mass component (f_m) varies from place to place depending on the distance from the centre of the Earth. At the equator the centrifugal component is at a maximum, and at the geographic poles it is zero.

Gravity at points on the Earth surface varies with position due mainly to: change in the centrifugal component with latitude, non-spherical (ellipsoidal) shape of the Earth, and local variations of density within the Earth.

Gravity varies with respect to:
Height above sea level - by about 300 microgal/m
Latitude - by 0 (poles) to about 0.8 microgal/m (at about 45°S)
Longitude - by < 0.01 microgal/m

2.3 Variations with time (Longman, 1959; Broucke et al., 1982; Melchior, 1983; Torge, 1989)

For relatively short periods of time (< 100 years) the rate of rotation of the Earth, and hence the centrifugal component at a point, is constant, although over geological time periods the rate of rotation (angular velocity) may have slowly decreased due to frictional drag of water in the oceans.

The mass component at a point changes with time, due mainly to changes in position of the Sun and Moon relative to the Earth. The maximum amplitude of the gravity changes is 240 microgal, and the maximum rate of change is about 50 microgal/hour. Changes due to motion of other celestial bodies are negligible (< 1 microgal).

Since the relative paths of the Earth, Moon and Sun are well known from astronomical observations, the gravitational effect at any point of the Earth's surface at any time can be predicted. These gravity changes are called the Earth-tide effect. The effect is periodic, being produced by the same force that produces the ocean tides.

Gravity variations associated with the exploitation of geothermal fields are similar in amplitude to the Earth-tide effect, and so the latter must be corrected for in order to isolate exploitation induced variations. Corrections using standard tidal prediction tables or computer programs are usually of sufficient accuracy. Three complicating factors need to be addressed when applying a tidal correction to gravity data in which variations of less than 10 microgal are being investigated:

a) The predicted tidal effect on a spherical solid Earth needs to be multiplied by the *amplification factor* to give a closer approximation to the effect on a real (elastic) Earth. The magnitude of the elastic contribution is determined by the distribution and tidal redistribution of mass below the surface, and is also latitude dependent because of the Earth's oblateness and the Coriolis force. The average value of the gravimetric factor is 1.16, with a normal range of 1.155 - 1.165.

b) *Phase differences* or *phase lag* of -6° to + 3° between observed "elastic Earth" and the predicted "solid Earth" tides result from the non-instantaneous response of the oceans (due to inertial and sea-bottom topography effects).

c) The *ocean loading effect* is caused by a combination of tilting of tectonic plates as the water mass distribution in the oceans varies tidally, and variation in the gravitational attraction of this varying water mass. Together, these may account for up to 4% of the *observed* Earth tide, in coastal regions, i.e. up to 10 microgal.

Each of these factors can be quantified, for a particular location, by recording gravity continuously for a period of 3-12 months and comparing the observed combined tidal amplitudes and phases with the predicted solid Earth-tide Effect. In general, however, it is adequate for most microgravity surveys in geothermal fields to take the predicted tide, multiplied by the standard gravimetric factor (1.16), in order to calculate the Earth-tide correction.

In terms of errors introduced by incorrect tidal corrections, timing is the most critical since tidal gravity varies by as much as 1 microgal/min. Errors in the tidal correction due to poorly specified station locations (latitude, longitude and elevation) are less important, provided elevations are known to a few hundred metres and horizontal coordinates to a few kilometres. With suitable attention to these factors (particularly timing) the error in the tidal correction can be reduced to be less than 1 microgal.

It is important when comparing the results of different surveys over the same geothermal field, that the surveys have been reduced using the same parameters to avoid introduction of a bias.

2.4 Changes in position of mass in the Earth

Such changes can occur over time periods ranging from several minutes to several years and may result from:

- *Mass changes* in geothermal or petroleum reservoirs as a result of exploitation.
- *Atmospheric pressure variations* associated with weather; i.e. the lateral movement of high- and low-pressure air masses. Air pressure changes during or between surveys generally do not exceed 10 hPa (10 mbar), and are commonly less than 5 hPa, so these effects are rarely more than about 2 microgal in amplitude.
- *Variations in shallow groundwater level.*
- *Variations in soil moisture*. Rainfall can also cause an increase in saturation of the aeration zone as fluid percolates down from the surface. During a long dry period there may be a decrease in saturation due to evaporation from the ground surface, evapo-transpiration from plants, or simple downward percolation of fluid under gravity.

- *Active volcanism.* Emplacement of magma at shallow depths, or changes in the degree of vesiculation of magma in shallow magma bodies. Gravity changes of up to 400 microgal have been reported.
- *Mining operations.* Removal of mineral ore, coal, and rock from underground mines will cause gravity changes at the ground surface above the area of excavation.
- *Topographic changes.* Changes in surface topography, such as associated with road or canal construction, can cause local, but significant, gravity changes.
- *Ground subsidence* as a result *of fluid withdrawal.*

Movement of people or vehicles do not cause measurable changes in gravity because their mass is too small, although they may cause ground vibrations which influence gravity measurements.

3. GRAVITY MEASUREMENTS

The small magnitude of the gravity changes of interest for microgravity surveying require high-precision instrumentation, together with careful field practice and analysis techniques

3.1 Types of gravity meters

There are two types of instruments used for measuring gravity in the field (c.f. laboratory):

a) Absolute instruments - these measure the absolute value of gravity at a point.
b) Relative instruments - these measure differences in gravity between points.

Absolute gravity measurements are generally based on the determination of the fundamental quantities of acceleration (distance and time) from the free movement of a sensor in the Earth's gravity field. Currently, the free-fall method is commonly used; pendulum methods have largely ceased. The best absolute instruments can measure gravity with an error of about ±10 microgal, which is sufficient for microgravity work in geothermal systems, but such instruments are not portable. At present, semi-portable instruments can reach an accuracy of ±50 microgal, but they are large and slow to set up and use. Absolute instruments currently available are therefore unsuitable for microgravity surveys in geothermal systems. For further details of absolute instruments see Torge (1989).

Relative instruments such as those manufactured by LaCoste & Romberg (LCR) and Scintrex are the only readily available ones with the portability, ruggedness and precision suitable for microgravity surveys. The LaCoste & Romberg D- and G-type gravity meters are astatic meters which function like a long-period seismograph. A mass on the end of a beam is held in place at one end by a supporting beam, and is balanced by a stretched metal spring. The spring is set up in such a way that its extension is equal to the distance between the points at which its ends are fixed. It behaves as a "zero-length" spring because its length, which is defined as its real (unstretched) length minus its extension is zero. In reality it does not shrink away to nothing when no force is put onto the beam, because the spring is always under stress since it is coiled. When the torque on the mass (from the force of gravity) is perfectly balanced by the torque from the spring, the net torque on the mass becomes zero. In this case, the mass exhibits simple harmonic motion, but the period tends to infinity and the equilibrium is said to be unstable. Readings are taken visually by nulling a beam to a zero-point.

The Scintrex CG-3M instrument is a microprocessor-based automated gravity meter (Budetta and Carbone, 1997; Bonvalot et al., 1998). The gravity sensor consists of a proof mass suspended by a quartz spring, and there is a capacitive displacement transducer feedback system to move the mass back to a null position. Measurements are begun by pressing a key and readings are automatically made for a specified time or number. Readings are displayed on an LCD unit and stored in a digital memory, which allows each reading to be compared with the average of those already taken and stored or rejected. The Scintrex CG-3M instrument also has automatic corrections for tilting during the measurement sequence and drift.

Scintrex instruments are easier than LaCoste & Romberg for inexperienced operators to use, but suffer more from instrumental drift and calibration problems.

3.2 Tares

A tare is a sudden (< 1 s - 1 min) apparent jump in instrument reading (Torge, 1989). This may range in amplitude from a few microgal (limit of detection) to several milligal, and is an important and serious source of error in microgravity surveys using spring-type relative gravity meters. Both LaCoste & Romberg and Scintrex CG-3M gravity meters are subject to tares but the LCR instruments are much more susceptible to these. A tare is basically a jump in the zero point of the meter, and the change can be in either direction (increase or decrease in reading). There are two main types of tare:

a) **Thermal tares -** these occur when the thermostat and heater in the meter are unable to adjust the internal temperature to rapid external temperature changes. Such effects are likely to occur when the meter is removed from the carrying case into a cold environment, or conversely. To minimise the chances of this happening, the inside of the transport vehicle should be kept at a similar temperature to that outside (i.e. do not use heater or air-conditioner). Other causes of thermal tares can be poor battery contacts and damaged power supply cable. Even a drop of a fraction of a degree in temperature inside the instrument, for only a few minutes, will cause the apparent reading to drift for several hours and may result in a thermal tare.

b) **Mechanical tares -** these occur when a LaCoste & Romberg meter is knocked or jolted, either in a "clamped" or "unclamped" state; knocks to the meter when "unclamped" will result in larger tares than for similar knocks when "clamped". Special care must be taken, when removing or returning the meter to the carrying case, not to knock the legs (levelling screws) against the case (or its lid). Another common cause of a mechanical tare is dropping an object (pen, glasses, field book) on to the top of the meter during a reading.

It is very important that any incidents which might cause a tare, and the time at which they occur, are recorded to enable adjustments to be made during reduction of the data. Field experience suggests there is not necessarily a direct relationship between the size of the knock and the size of the tare induced; a small knock may induce a large (>50 microgal) tare, but a large knock will almost certainly induce a large tare. Tares can be minimised by careful field technique, but it is unusual for a survey of more than a few days to be completed without a tare occurring. If the meter is knocked then further (repeat) readings should be made as soon as possible at survey points recently occupied; this greatly assists in the accurate determination of the size of the tare.

3.3 Instrument drift

In spring type gravity meters, the readings at a point (corrected for the Earth-tide effect) will change slowly with time as a result of ageing of the springs in the meter, and this is called instrument drift. It can be considered as a slow and regular change of the zero point of the instrument. It is determined for each meter from the change in gravity at repeated points, after correcting for the effects of earth-tides and tares. Drift is generally assumed to be linear with time. La Coste & Romberg instruments may have drift rates of 50 microgal/day when new, but this reduces to less than 5 microgal/day after a few years. Scintrex instruments have much larger drift rates which are automatically compensated for during the (internal) reduction of the data., however, field experience shows that for microgravity work it is best to determine the drift independently of the microprocessor and apply a correction to each set of observations.

If preliminary calculations show that there is a large apparent drift rate (>100 microgal/day) then the observations and their residuals should be examined closely for tares. If the apparent drift rate exceeds 500 microgal/day, consideration should be given to repeating the observations. If consistently high drift rates occur then it is probable that the meter needs repairing. It is therefore desirable to use older meters for microgravity surveys, provided they have been well maintained.

3.4 Calibration

Relative gravity meters do not give a direct measurement of gravity, or gravity difference. For LaCoste & Romberg meters the instrument (dial) readings are converted to values of gravity, or strictly differences in readings to differences in gravity, by way of a calibration scale unique to each meter. A calibration scale is provided with each new meter by the manufacturer and is determined in the factory by temporarily adding small weights to the beam, and measurement of gravity at two absolute gravity stations. For LCR Model-G meters the calibration scale consists of a table of dial readings and gravity values, at 100 counter unit intervals (approx. 100 mgal). For LCR Model-D meters, the calibration scale is a single number. A plot of counter units against gravity value approximates a straight line. For most geophysical uses, such as making Bouguer anomaly surveys, this scale is sufficiently accurate and can be used for many years. However, this is insufficient for microgravity surveys, where very small differences are being sought, because the calibration varies with time as a result of ageing of the moving parts. One of the effects of ageing is to alter the slope of the calibration line. This effect can be corrected for by multiplying the gravity values in the calibration scale by a constant (at any one time), known as the Calibration correction factor (*f*), which has a value close to 1.00. This factor can be determined by making a survey along a calibration interval consisting of two (or more) points of accurately known gravity or gravity difference. Generally these points are incorporated in, or have been linked to, stations in the International Gravity Standardisation Net (IGNS 71).

Although the calibration line approximates a straight line, precise measurements show that in detail it is a wriggly or corrugated line (non-linear), unique to each meter. Most of the corrugations in the line are repetitive, and are the result of minor imperfections (eccentricities) in the manufacture of the gear wheels, in the measuring screw (micrometer), and in the levers connecting the screw to the beam. Experiments show that for G-meters (> G458) the non-linearities have periods of 1.00, 7.33, 36.67, 73.33 counter units, and for D-meters 0.1, 0.722, 1.625, 3.250 counter units. Errors arising from these imperfections are called periodic errors; they can be determined by rigorous measurements over a very accurately known gravity range, or by intercomparison with other gravity meters whose periodic errors have been determined. In some meters these errors may exceed 20 microgal. For most repeat surveys in geothermal fields the effects of periodic errors can be neglected, but those of changes in calibration with time cannot. Failure to account for the change in calibration with time (between surveys) may result in spurious gravity changes of more than 100 microgal. Before each survey the meter(s) should be run over a calibration interval (Δg_i) whose range of gravity values include those in the area of the geothermal field.

$$\textit{Calibration correction factor } (f) = \frac{\Delta g_i}{\Delta g_m}$$

Where Δg_m is the gravity difference measured over the interval assuming the manufacturers calibration scale (i.e. $f = 1$).

3.5 Reading procedure

In microgravity work it is very important that the same reading procedure is used at each point, and during each survey. No attempts should be made to hurry, or "short-cut", the reading procedure, and the observer should be kept free of physical distractions such as biting insects, radio music, uncomfortable reading positions. Experience has shown that measurements taken during poor weather conditions (rain, snow, extreme heat) are generally of poor quality and often need repeating.

4. SURVEY PROCEDURES

The aim of microgravity surveys is to precisely measure the value of gravity (g) at a point (x, y, z) at a specific time (t). This involves the precise measurement of gravity and removal or correction for spurious temporal effects that change the value of gravity. Survey procedures are used which maximise these requirements.

4.1 Network design

The principal aim of microgravity surveys in geothermal fields is to measure temporal gravity changes associated with exploitation. It is therefore important that the survey (measurement) points extend well beyond the area in which measurable exploitation-induced gravity changes occur. Assuming that any mass changes are confined to the field, then from simple calculations (finite plate) using mass extracted values, the extent of the points beyond the field can be estimated. For the Wairakei field (New Zealand), where most of the mass changes occur at depths of 100-500 m, such calculations show that the gravity effects of likely mass changes are undetectable (< 10 microgal) at distances of more than 2 km from the field. For geothermal fields in which exploitation causes significant mass changes at greater depths it is necessary to extend the survey points to greater distances beyond the field boundaries. In fields where it is known (or suspected) that production (or reinjection) causes mass changes outside the field then it is necessary to extend the survey points even further. Design of the network should ensure that about 20% of the survey points lie in places where there will be no measurable gravity changes. This is important because it allows for the position of the zero change contour to be well established; this is important for determining values for net mass change using Gauss's theorem (described later).

Survey points should be free from the effects of mechanically- or culturally-induced vibrations; away from main roads, pumps and other machinery. Survey points should not be on production/reinjection wellheads or well cellars (because they suffer from vibration and thermally-induced elevation changes), but experience has shown that some steam transmission pipeline supports are satisfactory. There should be easy road access to the survey points; so that the distance of hand-carrying the instrument is small. This not only minimises the chances of tares but ensures that the survey can be undertaken in the shortest possible time. Photographs and diagrams of each survey point should be made, and notes taken of the easiest and quickest way to get to the point.

During the development of a field (up to 30 years), engineering constructions (new pipelines, additional wells, and new roads) are added which result in the destruction of survey points. It is therefore important that in critical places, there is sufficient redundancy of survey points such that loss of some points does not significantly affect the usefulness of the microgravity programme. Construction engineers should be made aware of this problem so that, where necessary, new points can be established and gravity measurements made *before* destruction of old survey points. Ideally, the gravity difference between the old and new points should be measured before destruction of the old point.

Additional survey points should be positioned near places where gravity (mass) changes are likely to occur such as in areas of greatest mass production or reinjection, surface geothermal activity, and ground subsidence.

4.2 Survey points

It is of critical importance that survey points allow reoccupation of the point with a precision of ±0.5 cm vertically and ±1 cm horizontally, or better. The points should therefore be on permanent, concrete structures or benchmarks, and clearly identified by a pin and identification plate. The surface around the pin should be flat and horizontal, and made of concrete or other stable material; wooden steps or bare ground surfaces are unsuitable. To minimise the chances of damage to the survey point during construction work it is desirable to bury the survey points within a small, concrete-lined chamber.

4.3 Reference station

When computing (reducing) the gravity values from the instrument readings it is convenient to place all observations in terms of a reference or base station. Often this station will also be used to help determine instrument drift. Ideally, this reference station will be:

a) Easily accessible at the start and end of a day's observations;
b) Outside the field and in an area not affected by mass changes within the field, or shallow groundwater level fluctuations;
c) In a position unlikely to be damaged by engineering construction work;
d) In a position where it can easily be incorporated in levelling surveys associated with the geothermal field.

The possibility of the gravity values at the reference station changing with time (and hence systematic gravity differences at other survey points) can be checked by examining the gravity differences at other survey points distant from the field. Gravity changes at these points should be close to zero; if they are not then a base correction, obtained by averaging the differences at distant stations, can be applied.

4.4 Observation procedures

When using relative gravity meters, certain observation procedures are used to maximise the precision of calculating instrument drift and any tares which might occur, and to minimise the chances of measurement error.

- To improve determination of instrument drift, we assume that the drift rate can change (both in magnitude and direction) between successive days of observation, and after a tare. It is therefore important that at least two observations are made at most survey points during a day's work. However, a simple reversal of the measurement order should not be done. Experience suggests a near-random sequence is best. To improve the linkage between successive day's observations, it is important that each day's measurements contains observations at two or more survey points occupied the previous day.
- To improve determination of the magnitude of tares, when a tare is recognised or suspected during the survey then re-observations should be taken at one or (preferably) two survey points made immediately before the tare.
- To minimise the chances of measurement error influencing the results, at least three observations should be made at each survey point.
- It is customary, but not absolutely necessary, to start and finish one day's observations with readings at the reference station.

Measurements should be temporarily suspended if:

a) Long period seismic waves from an earthquake (teleseisms) make readings difficult. For large distant earthquakes these may continue for several hours.
b) The power supply to the gravity meter fails; this will cause the instrument to go "off-heat", and give erroneous readings. After reconnection to a stable power source, several hours should be allowed after the meter has re-established its operating temperature before observations are restarted. In reduction of the data, a power loss should be treated as a tare.
c) The gravity meter suffers (or is suspected to have) a large tare such as might result from it being dropped, or the transport vehicle is involved in a serious accident.

To avoid reader bias, the same observer and the same technique should be used throughout a survey. Experience has shown that the best results are obtained when a survey is carried out in a single, set of continuous daily observations. Breaks of several days or more during a survey generally result in poorer results (higher standard errors and residuals). Experience also shows that if the gravity meter has not been used for a long time before the start of the survey, then the first days observations may not be satisfactory and will need to be repeated.

To reduce the time between observations it is best if as many as possible of the survey marks are visited and prepared (vegetation and rubbish removed) before the measurement start. The measurements should be reduced as soon as possible, so that if remeasurements are required then the time gap between the main survey and the remeasurement survey is small.

4.5 Errors and blunders

Mistakes will occur during any set of gravity observations, and are called *blunders*. Few microgravity surveys are free from blunders, such as: occupation of the wrong survey point; transposition of numbers when recording the readings, forgetting to record all the data required (e.g. time), incorrect entry of data into the computer. Blunders are generally discovered during initial reduction of the observational data, and corrected using the redundancy of data available.

Errors are deviations from the correct or accurate measurement and are inherent in any set of observational data. Observations commonly have a normal or Gaussian distribution about the "true" value, and are random. However, some errors are consistently in one direction, and are known as bias.

A list of the main causes of errors is given in Table 5; most of these can be minimised (but not eliminated) by careful survey practices. If these practices are used, the main cause of large errors is that of tares. During reduction of the data, tares (both recognised and suspected) can be corrected for (see later) but those with an amplitude of less than about 20 microgal are difficult to determine and are generally neglected; in this case their effect is absorbed into the drift correction. Good estimates of the error of a gravity value at a survey point are given by the size of the residuals (differences between an individual observation and the mean at that point) and the standard error determined during reduction of the observational data. In a good survey these should be 5-10 microgal; a residual >20 microgal suggests a poor reading and may be discarded.

A good estimate of the error of gravity changes (differences in gravity between surveys, corrected for elevation and groundwater variations etc.) can be obtained from the standard deviation of the mean of changes at survey points located well outside the geothermal field. However, care must be taken to exclude data from survey points known or suspected to be located near any areas from which recharge fluid may have been withdrawn or reinjected fluid may have been deposited. Also excluded, must be data at points where a blunder has occurred, such as failure to reoccupy the same point.

5. INFRASTRUCTURE AND ORGANISATIONAL REQUIREMENTS

Conducting microgravity surveys require similar organisational support to other large geophysical surveys using advanced equipment (eg. MT, CSAMT, aeromagnetics). Good results will rarely be obtained from individuals working alone, or with inadequate support, or using gravity meters which have not been carefully used and maintained (eg. commercially hired instruments used extensively on prospecting surveys). Basic requirements are listed below.

TABLE 5: Summary of external, instrumental and reading errors associated with use of LaCoste and Romberg model G gravity meter (from Rymer, 1989)

Cause	Comments	Approx. size of error	
		maximum	**minimum**
External			
Earth tide amplification factor	Value ranges from 1.155 to 1.165 depending on Love numbers and latitude	< 2 µgal	< 1 µgal
Phase lag	Observed and predicted tides may be out of phase by -6° to +3°	Unknown but small	(< 1 µgal)
Ocean loading	Caused by tilting the shoreline and the gravitational attraction of mass of water in the oceans	< 10 µgal	1 µgal
Noise	Low frequency (< 1 Hz) disturbances caused by wind, surf, and distant earthquakes cause beam to swing: also produce tares	< 50 µgal	1 µgal
Reading			
Leg length	Height of meter is varied by changing leg lengths, gravity varies according to the free air gradient of -3 μGal cm^{-1}	10 µgal	< 1 µgal
Sensitivity and levelling	Sensitivity can be varied manually, but it drifts with time. Failure to level, especially along the long level, effective-ly changes the reading line and changes the sensitivity.	< 20 µgal	
Dial movements	Slack (backlash) in the gears will cause errors unless the reading is approached from the same side each time	< 40 µgal	< 1 µgal
Timing	Provided the reading is steady, there is no evidence that there is an advantage in waiting before making a reading	Negligible	-
Instrumental			
Movement of instrument	The rms deviation about the mean reading when the gravity meter is moved between readings is greater than if it is not moved between readings		
Meter calibration	Polynomials and Fourier series can be used to model the calibration features. There are periodic terms due to the way the LCR is constructed, but over small ranges the effect can be kept down to a few microgals.	500 µgal in 500 mgal or 0.1%	< 1 µgal
Thermally-induced tares	Low battery power or a sudden change in external temperature may cause a thermal shock to the measuring system unless a secondary thermostat is fitted. If the internal temperature is allowed to fall to room temperature the effect is much larger.	~ 10 mgal	
Shock-induced tares	Hysteresis effects in the spring and physical jolting of the system can cause tares of almost any magnitude	~ 10 mgal	< 1 µgal
Total		50 µgal to several mgal	< 10 µgal

5.1 Field staff

Staff should be trained in the use of high precision gravimetry, and understand the principles involved. Although experience in making Bouguer anomaly type of gravity surveys is helpful, this is not sufficient training because of the increased care and knowledge needed for microgravity measurements. Field staff should be meticulous in making and recording the data. Staff should be encouraged to immediately report or record all mistakes; it should be made quite clear to them that this is important and that no punitive action will result from unintentional mistakes. During the survey, staff must be under no pressure to complete work by a specific time or date. The taking of gravity measurements must be the prime, and only job, being carried out. New staff should serve an "apprenticeship" with an experienced person.

5.2 Equipment

The gravity meter should be one which has been carefully maintained and whose history is known. Meters rented from commercial geophysical supply companies are not suitable; their maintenance history is not known (seals may be defective; magnetic shielding may have been reduced) and they are likely to have been used in severe operating conditions. Whenever possible, the same instrument, and the same operator, should be used in successive surveys. Equipment should be transported in a well-maintained 4-wheel drive vehicle, preferably fitted with a sprung carrying box for the instruments. The vehicle should not be driven at high speed over rough roads; the driver should be aware that jolting during transport is a major cause of poor results (tares) and will result in repeat measurements having to be made. Good maps and survey point location diagrams are needed.

5.3 Office staff and facilities

Staff involved in reduction of the gravity data should be experienced in gravity data and its collection; this is important because it enables them to recognise and correct simple mistakes made in the field (e.g. transposition of numbers during recording of field data). Reduction of data should take place during or immediately after the survey. This enables dubious or unusual data to be checked or remeasured as quickly as possible.

6. REDUCTION OF GRAVITY OBSERVATIONS

To determine the value of gravity at a survey point (observed g) the meter readings must be converted into gravity values (using calibration data), and corrections made for short-term temporal effects (Earth-tide, instrument drift, and tares). A number of computer programs are available to do this.

In New Zealand, a program is used in which the whole set of observational data for a survey is taken and the values of relative gravity (at each point) are calculated using the Least squares method. The readings themselves, and not the differences between successive readings, are used for the observation equations. Using this program for reduction of the observational data, to provide values of observed gravity (or strictly gravity difference with respect to an arbitrary base value) is an iterative process which involves subjective judgements by the person running the program. The first step is to locate mistakes in the input data file caused by (in approximate order of likelihood): mistakes in entering the field data into the computer, mistakes in recording the field data, malfunction of the gravity meter. The program is first run, with large values adopted for the blunder rates (say 0.1) and standard errors (say 0.5). Such mistakes will quickly become apparent and be signalled by very large residuals (>20 microgal), high daily drift rates (>500 microgal/day), or failure of the program to complete the calculations. The next step is to start progressively reducing the values for blunder rates and expected standard errors, and begin searching for unrecognised (in the field) tares. Such tares show as sudden changes in the sign and amplitude of residuals, and by the presence of high drift rates. At this point it may also be decided to remove certain individual observations which do not appear to be in error, but they have large (>30 microgal) residuals. However, it is unlikely that more than 1% of the observations in a survey will fall into this category. Finally, we begin weighting the iterative process, starting with limits of 0.5 and progressively reducing to 0.01, or until the values of observed g do not change significantly (< say 2 microgal) between runs. At this stage a "satisfactory solution" has been obtained

7. GRAVITY DIFFERENCES

Gravity values at a point in a geothermal field often differ between surveys. These differences (apart from instrumental and reading errors) may result from (in approximate order of magnitude):

- Mass changes in the geothermal reservoir (what we seek to determine);
- Vertical ground movements (subsidence or inflation);
- Changes in groundwater level;
- Changes in saturation (soil moisture content) in the aeration zone;
- Local topographic changes;
- Horizontal ground movements;
- Changes in gravity at the base station.

Gravity values may also vary with time as a result of deep-seated regional mass movements (active volcanism) but because geothermal fields generally occupy a relatively small area, and the difference in time between surveys is relatively short, the gravity effects of such movements are usually small and can be neglected.

The gravity effects of mass movements in the geothermal reservoir, called *gravity changes* (or "corrected gravity differences"), are obtained by correcting the observed gravity differences for the effects of ground movements, and changes in groundwater level and soil moisture.

7.1 Vertical ground movements

Exploitation of a geothermal system often causes vertical ground movements; generally subsidence in or near to production areas, and sometimes inflation near to reinjection wells. The size and location of these movements are not predictable, and can only be determined by repeat levelling surveys. The largest movements are generally ground subsidence; in one area of the Wairakei field, subsidence (over a 30 year period) has exceeded 15 m, but inflation has been less than 0.01 m.

Assuming (initially) that there are no mass changes involved, the effect of ground movement at a point is to move the gravity meter through the Earth's gravity field: Subsidence will result in the instrument being brought closer to the centre of mass of the Earth thus increasing the apparent value of gravity, and conversely inflation will decrease the value of gravity. The size of this increase or decrease (Δg_v) will be governed by the *vertical gravity gradient* (*dg/dz*) in the vicinity of the point.

$$\Delta g_v = \frac{dg}{dz}\Delta h$$

where Δh is the amount of subsidence or inflation, and Δh is small (i.e. changes in the gradient can be neglected). As a first approximation, the vertical gradient can be determined from the gravity field of the reference ellipsoid derived from world-wide gravity measurements. This yields a value of -308.6 microgal/m (at sea level, lat. 45°); this is the value commonly employed as the *free-air correction* in Bouguer anomaly surveys.

However, the vertical gradient varies from place to place (by up to 10%) depending on the latitude and elevation of the point, and on the mass distribution (topography and geology) near the point. Values for the vertical gradient can be determined by making gravity measurements at two (or more) different heights at a place. To obtain values for the gravity gradient with sufficient precision it is generally necessary to have a vertical separation of 1 m (or greater) between the upper and lower measurement points.

Note that in correcting the observed gravity differences it is assumed that there is no mass change involved in the subsidence or inflation; the gravity effects of such mass change will therefore be incorporated or remain in the gravity change value determined and may need to be accounted for in interpretation of that change. Simple calculations, using reasonable models for mass changes during exploitation, indicate that the effects of exploitation have negligible effects on the value for the vertical gravity gradient at the surface; the value of the gradient is dominated by the mass attraction effect of the rock and immobile water.

7.2 Groundwater level changes

In many geothermal fields the hot reservoir is overlain, near the surface, by a cold groundwater system which in turn is overlain by a zone of aeration (vadose zone). Pores and fractures in rocks within the groundwater system are saturated with cold water, generally originating from percolation of rainfall (meteoric water) down through the aeration zone or lateral flow of groundwater.
In many places the groundwater level (i.e. boundary between groundwater and aeration zone) varies with time. Percolation of rainfall or snow melt downwards through the aeration zone may cause the groundwater level to rise. During periods of low rainfall, drought, or pumping from shallow wells (for irrigation purposes) the groundwater level may fall. In places with strongly seasonal rainfall the groundwater level may vary by 5-10 m over periods of a few weeks or months. The gravitational effects of such variations need to be corrected for.

The gravity effect (Δg_w), at a point on the ground surface, of a change in groundwater level (Δh) is given (Allis and Hunt, 1986; Torge, 1989) by:

$$\Delta g_w = 2\pi G \rho \varphi (1-S) \Delta h$$

where G = Gravitational constant (6.673×10^{-11} m^3 kg^{-1} s^{-2});
ρ = Density of the water (kg m^{-3});
φ = Effective porosity of the rock (dimensionless); and
S = Saturation (fraction of pore volume with liquid) in the aeration zone prior to the change (dimensionless).

In rocks with high permeability, S will generally approximate the residual saturation or specific retention; in rocks with low permeability, S will approximate the field capacity.

Ideally, groundwater level changes would be known from measurements in shallow wells alongside each survey point. However, drilling and monitoring of such a large number of wells is too costly. Instead, data from a smaller number of wells scattered throughout the geothermal field are used, and the value of groundwater level change is obtained by interpolating values from a map of water level change obtained by contouring this data.

7.3 Changes in saturation in the aeration zone

Rainfall or snow melting can result in an increase in saturation of the aeration zone (soil moisture content) as the fluid percolates down. During a long dry period there may be a decrease in saturation due to evaporation from the ground surface, evapo-transpiration from plants, or simple downward percolation of fluid under gravity. These effects can lead to significant mass changes with the aeration zone, and hence gravity changes at the surface.

The gravity effect (Δg_a), at a point on the ground surface, of a change in saturation (ΔS) in an aeration zone of thickness (d), is given by:

$$\Delta g_a = 2\pi G\rho\varphi\Delta Sd$$

Few studies have been made which quantify the changes in saturation with time in this zone. Makinen and Tattari (1991) measured gravity changes of about 12 microgal amplitude over periods of several months, associated with changes in soil moisture content of sand and silt at several places in Finland. Here, the amplitudes of the gravity changes were similar to those associated with changes in groundwater level. Ideally, therefore, measurements of soil moisture should be taken regularly, at the same time as depth of groundwater level. However, this is not a trivial matter, and requires use of Time Domain Reflectometry (TDR) equipment to measure changes in water saturation. A first approximation for the gravity effect would be to multiply the gravity effect of the (much more easily determined) groundwater level change, by a simple factor determined from TDR measurements at a few points.

7.4 Local topographical changes

Mass changes adjacent to one, or a few, survey points may occur as a result of engineering construction work in the geothermal field. Common situations are cutting or filling of road embankments, digging of drainage channels, and excavation of building sites. Generally, the gravity effects of these are negligible unless the construction is very large or very close (few metres) to the survey point. A correction value (Δg_t) can be estimated using terrain correction tables in standard geophysical prospecting text books, or using simple 2-D or 3-D computer programs.

7.5 Horizontal ground movements

Large vertical ground movements (subsidence) associated with exploitation may also be accompanied by horizontal ground movement. At Wairakei, horizontal movements of up to 1 m have been measured. Field tests suggest that the gravity effects of horizontal movements are negligible (< 1 microgal) because the nearby topography moves with the survey point. However, this is quite different from failure to accurately reposition the gravity meter over a survey point close to a topographic feature. In this case, large apparent gravity differences may occur because the instrument has been moved through a large horizontal gravity gradient associated with the nearby topography: such a case would be when the survey point is on top of, and near the edge, of a pier or pipeline support.

7.6 Base changes and correction

It is usual, when computing values of observed gravity from relative gravity meter data, to place the values in terms of a base or reference station having a fixed value which is assumed to be constant during the survey (apart from Earth-tide effects which are computed and accounted for). This assumption is generally valid because the time period for the survey is relatively short, and the base station is outside the geothermal field (and so not affected by temporal mass changes within the field or ground subsidence). However, the gravity value at the base may change between different surveys, due to a local variation in groundwater level. If this happens, and the same base value is used in the data reduction, then the gravity differences at all other stations will be changed by this amount; i.e. the differences will be biassed. One way of checking and correcting for this bias is to examine the gravity differences at survey points well outside the geothermal field. If there has been no gravity change at the base, then the mean of gravity changes at these points should be zero, or less than the standard error of the gravity differences (generally < 5 microgal). If the mean value exceeds the standard error then a base correction should be applied such that the mean becomes zero.

7.7 Calculation of gravity change

The gravity change, at a point, is obtained using the equation:

$$\Delta g \; = \; (g_2 - g_1) + (dg/dz)h + \Delta g_w + \Delta g_a + \Delta g_t + b$$

where g_1,and g_2 are the values of observed gravity for survey times t_1, and t_2; (dg/dz) is the vertical gravity gradient; Δh is elevation change; Δg_w is the gravity effect of local groundwater level changes; Δg_a is the gravity effect of changes in soil moisture; Δg_t is the gravity effect of local topographic changes; and b is the base correction.

The values of gravity change (Δg), for the period $(t_2\text{-}t_1)$ are the prime quantities involved in microgravity analysis of exploitation-induced changes.

8. GRAVITY CHANGES

The main causes of gravity changes, associated with exploitation of a liquid-dominated geothermal reservoir are:

- Liquid (pressure) drawdown in the 2-phase zone;
- Saturation changes in the 2-phase zone;
- Changes in liquid density due to temperature changes.

These three physical causes of mass change combine to produce most of the gravity changes observed during exploitation of liquid-dominated geothermal systems. Note, however, that these are not independent of each other.

The gravity effects of pressure-induced liquid density changes, pore compaction, and mineral precipitation are generally insignificant (< 10 microgal), and can be neglected (Allis and Hunt, 1986).

8.1 Liquid drawdown

A primary effect of withdrawing fluid from a geothermal reservoir is the formation of a 2-phase zone near the top of the reservoir, and subsequent drawdown of the deep liquid level (Allis and Hunt, 1986). Downhole pressure and temperature measurements, and gravity change data, together with numerical simulation modelling (Hunt & Kissling, 1994), indicate that during initial exploitation this 2-phase zone quickly expands laterally and vertically, although the greatest vertical expansion is likely to be in the vicinity of the production bores.

If S_o is the residual saturation after drawdown, φ is the connected porosity, ρ_s is the steam density, ρ_w is the liquid water density, and G is the Universal gravitational constant, then the gravity change (Δg) due to drawdown of the deep liquid level is:

$$\Delta g \; = \; -2\pi G\varphi(\rho_w - \rho_s)(1 - S_o)h$$

where h = Thickness (or change in thickness) of the 2-phase zone.

This 1-d equation, derived by Allis and Hunt (1986), is valid provided, the lateral extent of 2-phase zone is large compared with its depth, connected porosity and saturation change are uniform, and temperature is uniform in the zone.

The main uncertainties which might affect the calculation are likely to be in the values adopted for φ, Δ*S*, and *h*. Values for connected porosity (φ) may vary by 10 or even 20% within and between adjacent rock units. Saturation changes are also likely to vary both laterally and vertically within the 2-phase zone (Hunt, 1988), but the maximum value will be set by the residual saturation (S_o).

$$\Delta S_{(max)} = (1 - S_o)$$

Data from Wairakei suggest that here S_o is likely to be about 0.5; note the large amount of immobile water this value represents. The value of h is difficult to determine because the deep liquid level (the point at which no vapour is present in the interstices): ($S = 1$) is difficult to locate. Indeed, there may be no point at which this occurs because steam may be present in large fractures to considerable depth. Despite these limitations, calculations using "best estimate" values for these parameters at Wairakei provided results consistent with other data. For example, taking $\varphi = 0.3$, $\rho_w - \rho_s = 850$ kg/m^3, $\Delta S = 0.5$, and $h = 100$ m, the expected gravity change is about -550 microgal, similar to that observed during the early stages of exploitation (Allis and Hunt, 1986).

8.2 Saturation changes

Data from well bores suggests that as exploitation proceeds, pressures in the 2-phase zone vary (increase or decrease) both in time and space as a result of:

a) Steam loss due to boiling (dry-out), which causes saturation to decrease, which involves mass decrease and hence gravity decreases;
b) Cooling and condensation resulting from inflowing water, which causes saturation to increase, which involves mass increase and hence gravity increases.

Experience suggests that saturation in the 2-phase zone will decrease over a wide area as exploitation proceeds, and will gradually approach residual saturation (S_o). However, in places, the pressure decrease will cause inflows of replacement water which are cooler and may result in local increases in saturation.

The gravity changes associated with a saturation change are given, as a first approximation, by

$$\Delta g = 2\pi G \varphi (\rho_w - \rho_s) \Delta S\, h$$

8.3 Changes in liquid density due to temperature changes

If the density of water in an aquifer changes due to a temperature change and no saturation change results (i.e. the aquifer is confined and the liquid volume remains constant), the resulting gravity change will be

$$\Delta g = 2\pi G \varphi \Delta\rho h$$

where Δρ = Average density change; and
h = Average aquifer thickness with changed temperature Δ*T*.

At about 200°C, the volumetric coefficient of thermal expansion for water is almost 2 orders of magnitude greater than that of rock, so the effects of changes in volume of rock can be ignored. For temperatures between 180 and 230°C, $\Delta\rho = 1.3 \times 10^{-3}\, \Delta T$. Taking $\varphi = 0.3$, the gravity effect is

$$\Delta g(microgal) = 0.015\, \Delta T h$$

where *h* is in metres, and Δ*T* is in °C. If the temperature of a 500 m thick aquifer decreases by an average 10°C in the temperature range 180-230°C, gravity will increase by about 75 microgal.

The uncertainties with this calculation are whether the aquifer is confined, and whether saturation changes could have occurred because of change in the vertical pressure gradient over some portion of the liquid column. If an increase in density due to a temperature decrease causes the water level (or a steam-water interface within the aquifer) to fall, then the calculated gravity increase will be overestimated. The amount of overestimation will be proportional to the value of $(1 - S_o)$ in the unsaturated zone above the changing water level.

The extent to which temperature changes cause changes in water level depends upon the permeability in the upper portion of the liquid-dominated zone. If there is a region of relatively high permeability near the water surface, then the pressure within this zone will control the height of the water surface. Pressure changes due to deeper temperature changes will be restricted to greater depth. Similarly, if there is low permeability near the water surface, then the underlying liquid column tends to be confined and there may be no changes in water level. The only circumstances favouring changes in water level are when there is good vertical permeability through the liquid column and when pressure in the column is controlled by good horizontal permeability beneath the zone of decreased temperature.

9. ANALYSIS OF GRAVITY CHANGE DATA

9.1 Determination of local areas of net mass loss/gain

Visual examination of a contour map of gravity changes for a period of time during which exploitation has occurred may show places where gravity has increased (net mass gain), decreased (net mass loss), or where there has been no change (at least not significantly greater than the error of the measurements). This map, when compared with a map showing the locations and amounts of mass withdrawal, may provide some useful information:

1. During the early stages of exploitation, when there may be formation and expansion of a 2-phase zone, the extent of gravity decreases will indicate the (minimum) extent of the 2-phase zone. This data can be very important where it provides information in areas of the field in which there are no drillholes. Indeed, microgravity data are probably the only surface measurements that will provide such information which is important in setting up, or verifying, numerical reservoir simulation models.

2. Comparison of gravity change and mass withdrawal maps may indicate, in a qualitative sense, the location of
   (a) places where fluid withdrawn has been completely recharged; here there will be no significant gravity changes despite mass withdrawal;
   (b) places distant from the borefield where fluid has been mined; here there will be significant gravity decreases;
   (c) places where reinjected fluid has moved to, and the path of that movement; here there will be significant gravity increases.

Such data, although strictly qualitative, quickly helps to give a picture of the mass movements that have occurred as a result of exploitation, and confirm or refute models derived from well-bore measurements which may be confined to only a small part of the field.

A good example is at Wairakei. Maps of gravity changes for various periods during development of the field are given in Figure 34, and a map showing the total measured changes up to 1994 is shown in Figure 35.

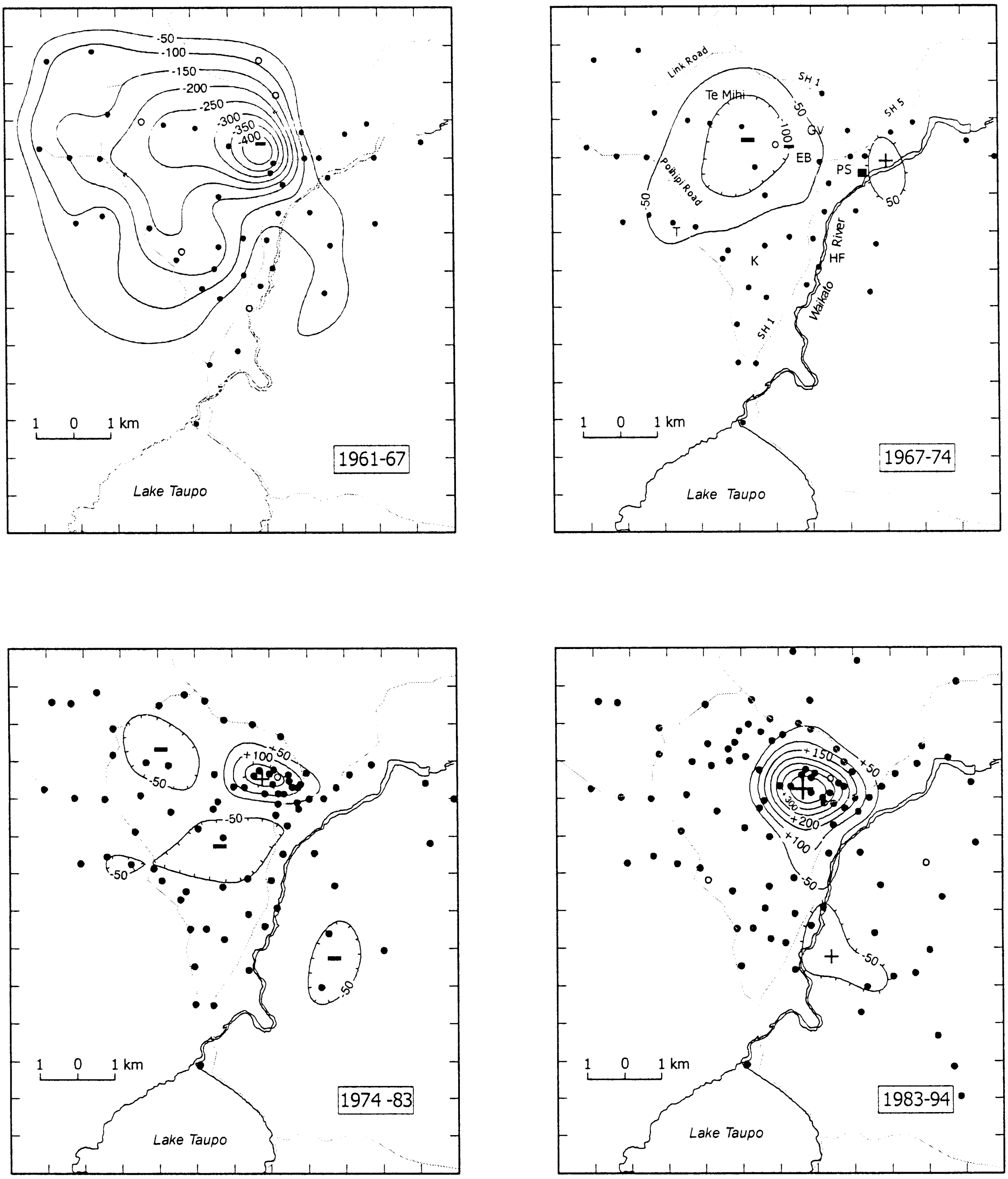

FIGURE 34: Gravity changes (corrected for ground subsidence) for various periods during the production period at Wairakei geothermal field, New Zealand. Contour values at 50 microgal intervals; zero contour has been omitted for clarity; solid dots are measurement used in contouring, open circles indicate measurements discarded. PS = Power station, EB = Eastern borefield, GV = Geyser valley, K = Karapiti thermal area, T = Tukairangi thermal area (Hunt, 1995 and updated)

9.2 Determination of recharge

The relation between the mass (M) of a body and its gravity effect is given by Gauss's theorem (Hammer, 1945; La Fehr, 1965):

$$M = \frac{1}{2\pi G}\iint_P g\,da$$

where G = Universal gravitational constant; and
g = The gravity value associated with an element of area a, over the plane of measurement P.

This formula is often used in mining geophysics to determine the (anomalous) mass associated with a Bouguer (or residual) anomaly. This formula can be extended (Hunt, 1970) to the case of a mass change (ΔM) and associated gravity changes dg:

$$\Delta M = \frac{1}{2\pi G}\iint dg\, da$$

To evaluate this integral, the simplest way (and sufficient considering the errors involved in the measurements) is to approximate the integral by a summation:

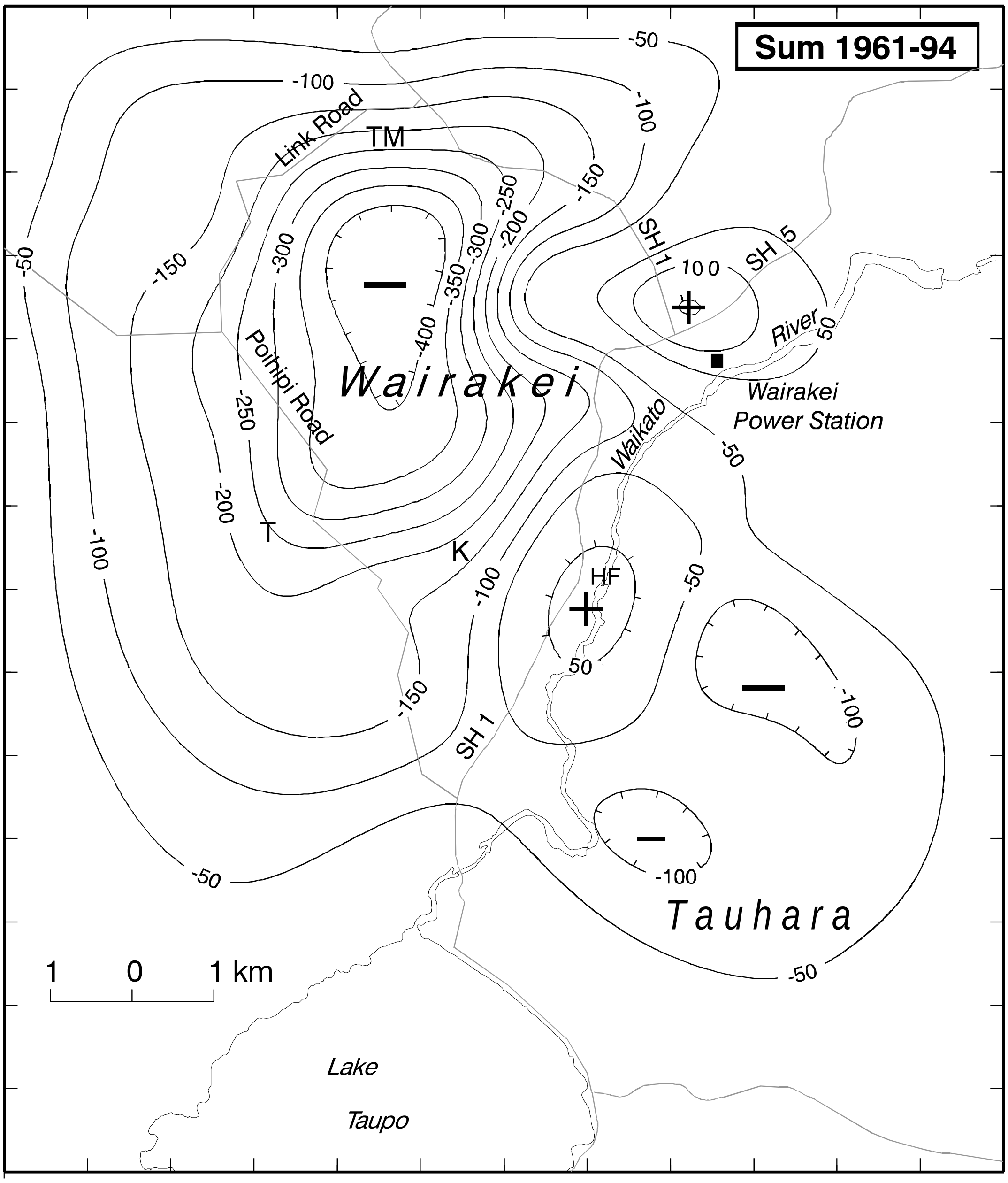

FIGURE 35: Sum of measured gravity changes from 1961 (first survey) to 1994 (last field- wide survey) at Wairakei geothermal field, New Zealand. Contour values at 50 microgal intervals; zero contour has been omitted for clarity. Map has been constructed by summation of 500 m grid values obtained from the maps in previous figure

$$\Delta M = \frac{1}{2\pi G} \sum \Delta g \, \Delta a$$

where Δg = Average gravity change in a small element of an area Δa, and the summation is extended over a wide area.

In practice, the summation can be made numerically using a computer program, or more commonly by gridding the gravity change map, estimating the average gravity change in each grid square, and summing these values to obtain $\Sigma\ \Delta g \Delta a$. In doing this it is important that the gravity data extends well beyond the region of measurable gravity changes associated with the field, and the area of each element is sufficiently small that the error in the estimate of Δg in the element is about the same as that of the measurement (and contouring) of Δg.

The value of ΔM obtained is the net mass loss/gain for the whole field for the period between the gravity surveys. *This method of determining the mass change is very powerful because it is completely independent of any assumptions about fluid density, depth of production, permeability, or porosity.* Its accuracy is limited only by the precision of the gravity measurements, and errors inherent in contouring and summing the data.

If the amount of mass withdrawn from the field by the wells (M_w), and any natural loss from surface discharge features (M_t) is known then the overall amount of mass recharge (R) can be determined

$$\Delta M = (M_w + M_t) - R \qquad \textit{and hence} \qquad R = (M_w + M_t) - \Delta M$$

During production, the mass withdrawn by the wells is usually much greater than that lost from the surface features, however the latter needs to be monitored because it may change with time. For example, at Wairakei natural loss before production was about 13 Mt/yr, but after 20 years of production had decreased to about 6 Mt/yr. Values for mass discharge and recharge for Wairakei, calculated by summation of the gravity changes, are given in Table 6 and have an estimated uncertainty of about 15%.

TABLE 6: Mass discharge and recharge values for Wairakei, MB is the mass withdrawn (M_t), MN the natural mass discharged, MT the total mass loss (MB+MN) is the integrated sum of gravity changes (N m^2/kg), MC the net mass change (M_t), and MR the mass recharge (M_t) (Hunt, 1995)

Period	MB	MN	MT	IS	MC	MR
1950-61	145	125	270	na	-100?	170
1961-67	360	55	415	-71	-235	180
1967-74	400	60	460	-13	-35	425
1974-83	390	45	435	0	0	435
1983-91	375	40	415	+19	+45	460

9.3 Testing numerical reservoir simulation models

Gravity change data can be used to discriminate between two (or more) numerical reservoir simulation models for exploitation of a field. The models predict development of a 2-phase zone and subsequent changes in saturation which involve assumptions about the geometry of the field, various reservoir properties, and behaviour of the field during exploitation. The models are generally developed progressively.

Prior to production, little information is available about response of the field to exploitation and generally only that resulting from test discharges can be used to set up the models. Under such circumstances it is likely that several different models can be devised which fit the data. If there has been sufficient mass withdrawal to cause gravity changes during the pre-production period it may be possible to test the models by calculating the predicted gravity effects and comparing them with measured gravity changes.

Discrepancies between the theoretical (model-derived) and measured gravity changes may indicate that assumptions made in setting up the models are wrong. Comparison of the theoretical and measured gravity changes should focus on the lateral extent and amplitude of the gravity changes. Large measured changes at points further away from the test discharge area may indicate values assumed (in the model) for permeability are too low, or for porosity are too high. This application of the microgravity technique may be particularly useful in the situation where the test wells are confined to a small part of the field.

The most favourable situation is where there is a period of field-wide test discharge, followed by a period of no (or limited) discharge so that any recovery can be monitored. Several gravity surveys during the discharge and recovery periods may provide sufficient information for discrimination between different simulation models. However, it should be recognised that the gravity changes are likely to be much smaller than those which may occur during the production period and consequently the precision of the gravity surveys, may need to be greater than for later surveys. This, in turn, may necessitate using fewer survey points, carefully chosen to maximise discrimination between the models. Natural discharges may be greater than the test discharges, and so need to be known accurately.

The technique was used to test initial models for the Broadlands (Ohaaki) field. It was found that changes in vapour saturation in the test discharge area were over-estimated, and their lateral extent was under-estimated (Hunt et al., 1990a). This led to the conclusion that the upper part of the production zone may be shallower, thinner, have greater porosity, and extend further than considered in the initial models.

9.4 Determination of saturation changes

Liquid saturation changes in a 2-phase zone as a result of boiling (dry out) or cooling and condensation during production can be determined for areas of the field if other variables (temperature change, liquid drawdown, and thickness) are known using the following basic 1-d equation:

$$\Delta g = 2\pi G \varphi (\rho_{w-s}) \Delta S h$$

However, saturation changes are best determined by using numerical reservoir simulation models, and varying the saturation change in appropriate blocks, until a match is obtained between the calculated and observed gravity changes.

9.5 Tracking the path of reinjected fluid

Reinjection involves the continuous transfer of waste liquid, generally back into the reservoir, and usually into a different part of the field from where it was withdrawn (production area). There is thus a transfer of mass from one place to another, and hence we might expect to observe a gravity increase in the vicinity of the reinjection wells. However, experience (tracer tests, pressure and temperature measurements) suggests that the reinjected liquid rarely remains in the vicinity of the reinjection wells. There are many scenarios for what happens to the reinjected fluid. Taking two simple cases:

1. *Reinjection into the 2-phase zone*
   The liquid is cooler and hence denser than the liquid present, and tends to sink towards the bottom of the zone. The process is complex: the cooler liquid will cause steam to condense, thus increasing the saturation in pores. Generally the rocks do not have isotropic permeability and so the liquid will move more rapidly along paths of high permeability and in response to any pressure gradients that might be present.

   The pattern of gravity increases associated with this process will therefore generally be non-uniform, and will reflect the directions of increased permeability and/or pressure gradients. Furthermore, by examination, and quantitative analysis of the gravity data from several repeat surveys it may be possible to determine the rate of flow of the reinjected fluid in particular directions. While the reinjected liquid remains in the 2-phase zone there will be a relatively large gravity signal because the liquid will be replacing vapour in the pores or fractures and hence there will be a large density change.

2. *Reinjection into the deep-liquid zone*
   Reinjection of relatively cool liquid into a hot, single-phase (liquid) zone beneath a 2-phase zone is more complex, and the effects will depend on the depth of reinjection below the deep-liquid level, the permeability (both vertical and horizontal) of the rocks, and the pumping pressure. Two extreme situations are:

   (a) The depth of reinjection is well below the deep-liquid level and vertical permeability is low. The reinjected liquid then flows out of the reinjection wells and displaces pore liquid horizontally. Although the reinjected fluid is cooler and hence denser than the displaced liquid, the density change is unlikely to be large enough to cause significant gravity changes at the surface. For example: if the reinjected water has a temperature of 150°C and completely displaces water at 250°C in the pores of a rock with porosity 0.3, then the density change is $(917 - 799) \times 0.3 = 35$ kg/m^3. Compare this with 150°C water displacing a similar volume of steam at 250°C: $(917 - 19) \times 0.3 = 269$ kg/m^3.

   Liquid water is (in this situation) incompressible, and so the displaced water must go somewhere. The most likely place for it to move to is laterally into the 2-phase zone; i.e. it will cause a lateral movement of the boundary of the 2-phase zone, some distance from the reinjection wells. At this point, liquid will replace steam in the pores and there will be a significant gravity change signal at the surface. The amplitude of the gravity changes will depend not only on the geometric situation, but also on what other changes are occurring in the reservoir in the vicinity of the 2-phase/1-phase boundary. However, the presence of localised gravity increases adjacent to (but not in) a reinjection area might signal the lateral flow of reinjected fluid from the reinjection wells to that point. Movement of such local gravity increases, between successive surveys, will reflect the direction of movement of the reinjected fluid.

   (b) The depth of reinjection is below the deep liquid level, and vertical permeability is relatively high. In this case the reinjected fluid will displace pore liquid vertically and the deep-liquid level will be displaced upwards in a cone of impression (this is the reverse of a cone of impression commonly found in groundwater surfaces around a pumped well). Generally the permeability of the rocks in and around the reinjection area will be anisotropic, and so the reinjected fluid will not flow symmetrically out from the reinjection area. This permeability anisotropy will cause the cone of impression to be similarly asymmetrical, indicating directions of greater and lesser permeability. At Wairakei, a cone of impression formed by such reinjection, was crescent-shaped, indicating increased flow in two, near-perpendicular directions (Hunt et al., 1990b).

3. *Injection outside the field*
   If the liquid is injected into or outside the field boundary then the liquid may not interact with the geothermal system. The ability for significant amounts of fluid to be injected outside the field indicates the presence of porous formations capable of absorbing the liquid. Such formations are likely to be highly porous and have low saturation; the injected fluid will replace air in the interstices and hence there will be a large density change (even neglecting cooling effects). Gravity changes (increases) in the vicinity of the reinjection area will therefore indicate the presence (location) of injected liquid, and changes in location between successive surveys will indicate migration of the injected liquid.

In the above cases, note that as the plume of injected fluid moves, the gravity changes will be associated only with the pores that have been saturated since the last survey; in previously saturated pores there will be no significant density change and hence no gravity change.

Quantitative analysis of the gravity data can be made using standard 3-d gravity modelling programs, provided values are known (or can be assumed) for: porosity, initial saturation, liquid density, and the geometry of the situation (depth or initial position of deep liquid level).

9.6 Determination of reservoir properties

Exploitation of a liquid-dominated geothermal system generally results in a transfer of mass (from one part of the field to another), which may cause measurable gravity changes. In some cases, the *rate* of mass transfer is controlled by the properties of the rock in the reservoir (e.g. permeability), hence the *rate* of gravity change with time is related to those properties. In such cases values for the properties can be determined from repeat microgravity measurements using numerical reservoir simulation models. Two such cases are the following:

1. *During formation and expansion of a 2-phase zone in the initial stages of production*
   Analysis of gravity changes at Wairakei geothermal field using simple radially symmetrical models and the MULKOM simulator showed that, for survey points near the centre of the production area, the size of theoretical changes soon (< 3 years) differs greatly (> 50 microgal) for different values of permeability (Hunt and Kissling, 1994). For example, after only 12 months the gravity change in the centre of the borefield is predicted to be -330 microgal for a permeability of 50 md and -180 microgal for a permeability of 200 md. Good estimates of permeability may be obtained by comparing the measured gravity changes with theoretical curves of gravity change calculated for different permeabilities, using a simple plot of gravity change against time. The analysis for Wairakei suggested that the gravity changes are most sensitive to differences in reservoir permeability at points close (< 1 km) to the production area (i.e. area of greatest liquid drawdown), but elsewhere are more model dependent (in particular to radius of the model). Application of this technique therefore depends on sufficient information being available to construct a realistic numerical simulation model, and a simulator which can generate theoretical gravity changes.

2. *During reinjection which causes displacement of the deep liquid level*
   As outlined above, reinjection may cause displacement of the deep-liquid level (vertically or laterally). Taking the case of vertical upward displacement of the deep liquid level, the shape of the cone of impression and its rate of growth (or decay, if reinjection stops) is controlled by the permeability of the rocks in that area. Note that the gravity signal reflects mainly the resaturation of the pores in the 2-phase zone; the effect of mass increase due to the denser (cooler) reinjected water at depth is small. By measuring the rate of change of size and shape of the cone of impression from several gravity surveys, and modelling this using a numerical simulator in which the permeability is adjusted until the measured and calculated gravity changes are in agreement, values for permeability (vertical, horizontal) can be determined. If the horizontal permeability is anisotropic, values for permeability in different directions may be calculated. Successful application of this technique will depend on the availability of adequate gravity change data in the vicinity of the reinjection well(s), including one or more baseline surveys to enable corrections to be made for other (more extensive) changes that might be occurring (such as a general rise or fall in the deep liquid level).

This technique was used at Wairakei during a reinjection test into an older part of the borefield. Using an analytical model (Theis or line source solution), values of 18.2 and 5.4 dm were obtained for permeability-thickness (kh) assuming anisotropic permeability (Hunt and Kissling, 1994). The modelling also provided a value of 8.7×10^{-6} m/Pa for storativity (φch).

10. CASE HISTORIES

Microgravity surveys have been made at more than 10 producing geothermal fields: *Wairakei, Ohaaki* and *Kawerau* in New Zealand; *Bulalo, Tiwi,* and *Tongonan* in the Philippines; *Larderello* and *Travale* in Italy; *Hatchobaru, Takigami* and *Yanaizu* in Japan. They have also been tried at *The Geysers* and *Heber* fields in USA, and at *Cerro Prieto* in Mexico, but apparently abandoned due to political considerations and lack of funding. It is rumoured that they have also been made in some other fields, but abandoned for a variety of reasons (chiefly poor measurement techniques and failure to install adequate survey marks) which have resulted in spurious results when the gravity changes between the first and second surveys have been calculated. However, this is exactly what happened at Wairakei in the early 1960s (Hunt, 1995), and it should not discourage use of the technique.

10.1 Wairakei (New Zealand)

Wairakei is a liquid-dominated field, located in the central part of the North Island. Test drilling began in 1950, and commissioning of the power station began in 1958 and continued until 1962, at which time the installed capacity was 193 MW (gross). There has been no significant reinjection; all waste water is discharged into the nearby Waikato River.

The technique of using repeat microgravity measurements to investigate the effects of exploitation of a geothermal field was developed using data from Wairakei. During nearly 40 years of production, 13 repeat surveys have been made. The first survey, however, was not made until 1961 (3 years after production began), and although carefully made, was not done to the now accepted requirements of precision or redundancy. Furthermore, few measurements of elevation or groundwater level change were made at that time. However, by the early 1970s significant improvements in gravity measurement and reduction techniques had been made, and monitoring programmes had been implemented. Early interpretations of the gravity change data clearly showed that the largest changes occurred during the early stages of development of the field and that during this time there was little natural recharge of fluid - the reservoir was being mined of fluid. The results of the 1961-67 and 1967-74 survey periods (Figure 34) showed the necessity for a comprehensive baseline survey to be made before production began. During the early 1980s, the microgravity results obtained at Wairakei, in conjunction with the reservoir engineering data enabled the various causes of gravity changes to be understood (Allis and Hunt, 1986).

The largest gravity changes have been in the Eastern borefield which formed part of the main production area during the early stages of development. Between 1961 and 1974, gravity values decreased by up to 560 microgal, but have subsequently increased by about 440 microgal (Figure 36). The decrease was caused by expansion of the 2-phase zone and dry-out of the upper part of this zone which has become vapour-dominated (Allis and Hunt, 1986). The subsequent increases have been attributed to re-saturation of the lower part of the 2-phase zone by downflows of cold groundwater; i.e. the deep liquid level has risen. In the late 1980s, environmental concerns necessitated a study of reinjection and a long-term (13-month) test was undertaken during 1988-89 in part of the borefield which had the greatest pressure decrease. Initial theoretical calculations suggested that there might be little gravity change associated with the reinjection and so a full study was not undertaken; instead gravity measurements were made only before and immediately after the test, and not during the test. This proved to be a mistake. There was a significant gravity change (+120 microgal) associated with the reinjection which on analysis showed that the reinjected fluid had flowed in two directions away from the reinjection bore (Hunt et al., 1990b). This led to an improved understanding of some of the physical processes involved in the 2-phase zone, and the realisation that in certain (but not unusual) circumstances the gravity changes could be related to physical properties of the reservoir and in particular permeability-thickness (kh) and storativity (φch) (Hunt and Kissling, 1994). If a more detailed gravity monitoring programme had been undertaken it might have been possible to better determine anisotropic values for kh. The results of the surveys during the reinjection trial also led to the concept that the permeability could be determined from gravity

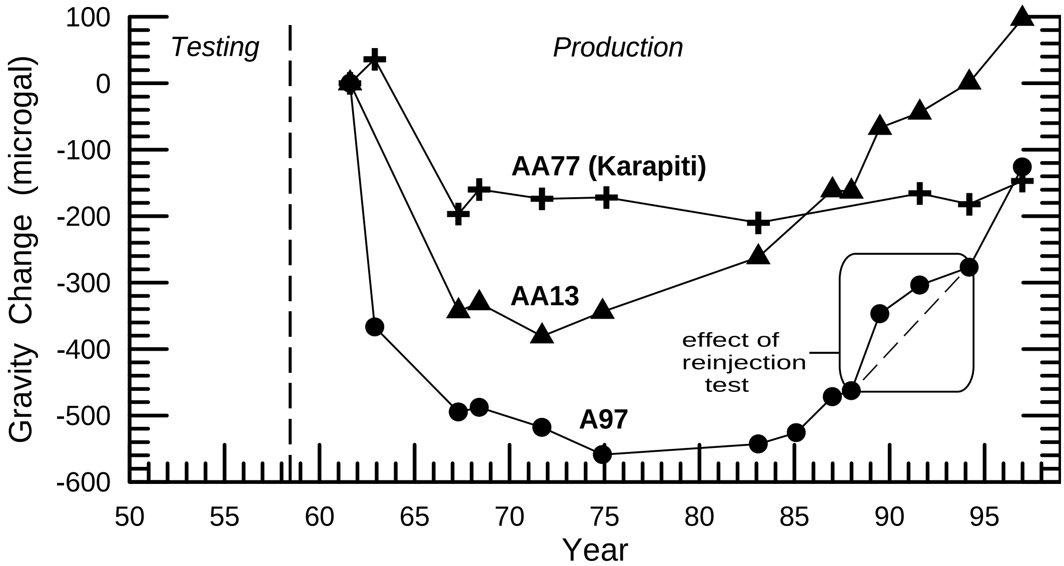

FIGURE 36: Gravity changes at selected benchmarks in Wairakei geothermal field, New Zealand. Benchmarks AA13 and A97 are in the Eastern borefield. Note the gravity decreases during the early stages of production as the 2-phase zone expanded, followed by the gravity increases as the deep water level in the Eastern borefield rose as the rocks became re-saturated as a result of cold downflows

measurements during the early stages of expansion of the 2-phase zone. Unfortunately, insufficient measurements had been made during these stages at Wairakei or Ohaaki fields; one measurement at Wairakei indicated a permeability of 100 md (Hunt and Kissling, 1994). We must now wait for sufficient measurements to be made in another field to fully test this concept.

10.2 Ohaaki (New Zealand)

Ohaaki (Broadlands) is a liquid-dominated field, situated 25 km north-east of Wairakei. Development of the field was unusual; a 4 year period (1967-1971) of large-scale test discharges (without reinjection) was followed by 16 years (1972-1988) of relatively minor discharges which allowed recovery of the field, before full-scale production (and reinjection) for a 116 MW (gross) power station was started in 1988. During the test discharge period deep-liquid pressures decreased by about 15 bar, but subsequently recovered by about 10 bar during the recovery period, before decreasing again when production began.

Seven, field-wide gravity surveys have been completed to date which span the test discharge, recovery and production periods. Gravity changes (max. -165 microgal) during the test discharge showed that there was little or no recharge during this period, and the field was effectively mined (Hunt, 1987). During the recovery period there were positive gravity changes within the field (up to +65 microgal) which indicate that natural recharge exceeded the small amount of mass withdrawn. Gravity change data for the drawdown and recovery periods were used to test 3 numerical reservoir simulation models for the field prior to production beginning (Hunt et al., 1990a). The models predicted changes in vapour (or liquid) saturation with time, and hence changes in density from which changes in gravity could be easily calculated. The results showed that none of the models adequately explained the microgravity data, suggesting that the upper part of production zone was shallower, thinner, had greater porosity, and extended further than considered by the models. This allowed the models to be refined before production began.

Since production began, large gravity changes (up to -200 microgal) have occurred in the central part of the field. The distribution of negative gravity changes within the field is similar to the temperature

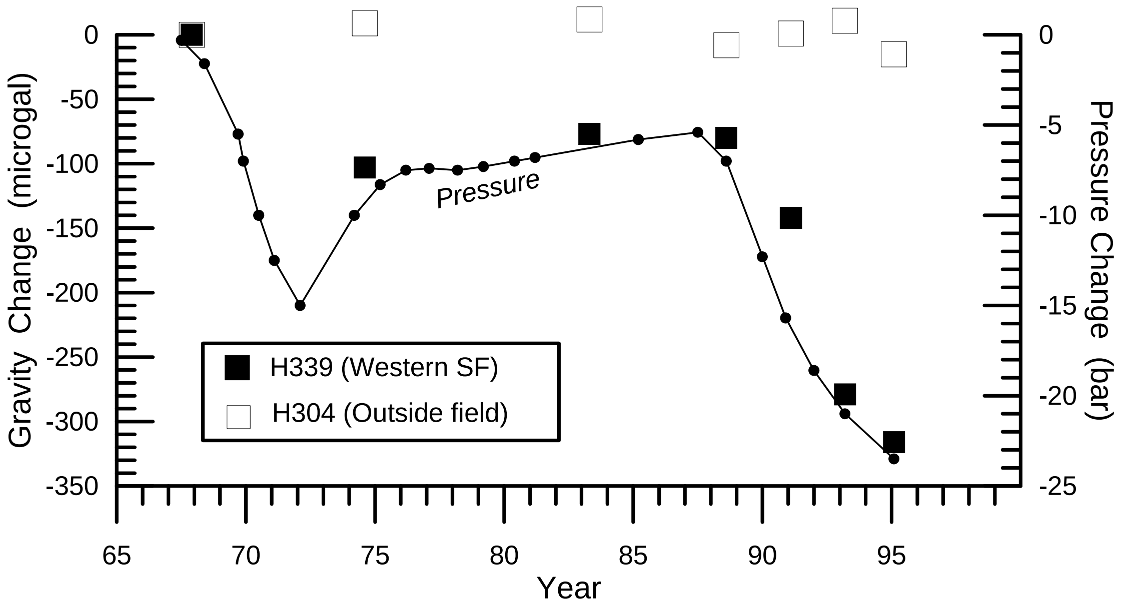

FIGURE 37: Gravity changes at benchmarks inside and outside the Ohaaki geothermal field. Note how the gravity changes at benchmark H339 (near centre of Western steamfield) follow the reservoir pressure changes

distribution at depth, and probably reflects mainly the extension (both horizontally and vertically) of the 2-phase zone in the reservoir, and reduction in saturation (dry-out) within this zone. This explanation is consistent with the gravity changes at benchmarks in the area of greatest change, which follow the trend in deep-liquid pressure declines in the production area (Figure 37). Despite 70 Mt having been reinjected around the edges of the field there have been no positive gravity changes in these areas indicating that the reinjected water has laterally displaced fluid near the reinjection wells. Analysis of the data (Hunt, 1997) indicates that natural recharge has been only about 5 Mt of the 31 Mt mass lost to the atmosphere (Figure 38).

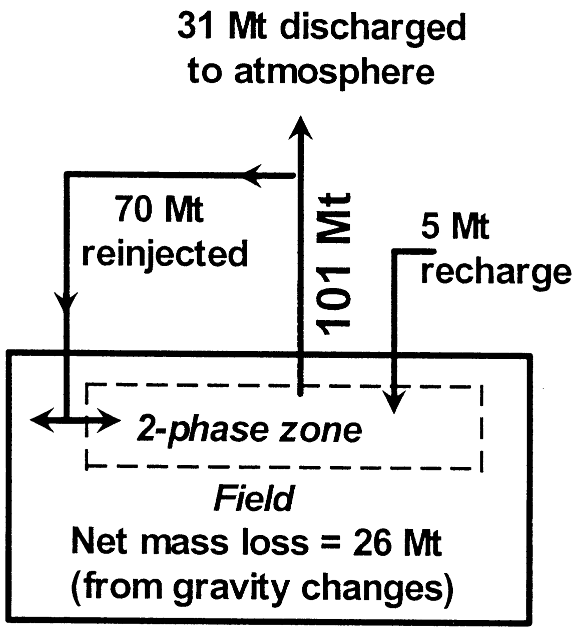

FIGURE 38: Block diagram summarising mass changes in the Ohaaki field during 1989-96, determined from microgravity measurements

10.3 Tongonan (Philippines)

This is a large, liquid-dominated field, located in Leyte Island. Development began in 1983 with the commissioning of a 37.5 M power station (Tongonan I). Since then a further 118 MW (Upper Mahio, in 1996) and 77 MW (Malitbog) have been added. Annual withdrawal rates increased from 5 Mt/yr in 1983 to 15.8 Mt/yr in 1994. By March 1995, a cumulative total of 131 Mt had been withdrawn of which 62 Mt had been reinjected.

Five microgravity surveys have been conducted (1980, 1981, 1982, 1985, 1995) at about 100 survey points. The most extensive and reliable data are for the 1981 and 1995 surveys. Erroneous levelling data precluded the interpretation of 1981-95 data, but if there was no ground subsidence then the gravity changes have been less than 50 microgal over all the field except in the Mahio area where changes of up to -75 microgal were measured (Apuada & Hunt, 1996).

10.4 Bulalo (Philippines)

Bulalo is a liquid-dominated field, located 70 km south-east of Manila. Production began in 1979 with an installed capacity of 110 MW, increased to 220 MW in 1980, 330 MW in 1984 and 426 MW in1996.

Fieldwide gravity and levelling surveys have been conducted every 1-3 years since 1980, and cover an area of about 36 km^2. The gravity measurements were initially made at 87 benchmarks, and the network has subsequently been increased to 120 measurement points (San Andres and Pedersen, 1993; Protacio et al., 2000). Bi-monthly gravity monitoring at six stations (1986-1987) indicated that the uncertainty due to non-reservoir causes is ±20 microgal, which is attributed to variations in rainfall and groundwater level. Surveys were usually conducted during the dry months of March, April and May to minimise the effects of rainfall. Selected benchmarks (up to 7 km from the centre of production) were used as fixed references for datum shift (base change) adjustments. Ground subsidence of up to 0.5 m has occurred, centred on the production area.

Between 1980 and 1991, gravity changes exceeded -250 microgal, and the maximum rate of change was -26 microgal/yr at a point near the centre of production. The cumulative gravity changes (1980-1999) have now reached almost –600 microgal in the central part of the production area. This sector has high excess steam indicating widespread on-going change from brine to steam. The smallest cumulative change in the production area is now more than –250 microgal. The gravity decreases within the production area have been near-uniform with time.

Mass discharges predicted by recent reservoir simulation modelling have generally matched those inferred from the observed gravity data. According to simulation studies, no recharge occurred between 1980 and 1984. The mass recharge between 1984 and 1991 was estimated to be 30% of net fluid withdrawal during the same period, equivalent to an average rate of 175 kg/s (630 t/hr). Calculations indicate that there has been about 42% recharge of the 374 Mt net mass loss since 1980 (Protacio et al., 2000).

10.5 Tiwi (Philippines)

Tiwi is liquid-dominated field situated 250 km south-east of Manila. Production began in 1979 with an installed capacity of 110 MW which was raised to 220 MW in 1980 and then to 330 MW in 1982. Total mass withdrawal peaked at about 38 Mt/yr in 1983, but by 1990 had fallen to 22 Mt/yr; reinjection began in 1983 and from then until 1990 has been about 9 Mt/yr.

Microgravity surveys began in 1979, and subsequent surveys were made in 1980, 1982, 1984, 1986, 1988 and 1990 (San Andres, 1992). Surveys have been made regularly since 1990 but the results have not been published.

The gravity data (San Andres, 1992) delineated areas of decreasing gravity over the production area, which were caused mainly by development of a steam zone. Initially, large gravity decreases were observed in the eastern Naglagbong area which provided most of the geothermal production. At the same time, significant gravity decreases also were observed in the Kap-Mat area in the west. This behaviour is consistent with a shallow hydraulic connection between these two areas. In the Kap-Mat area the general trend in gravity has been linear rate of decrease with time, consistent with expansion of the steam zone and increasing in vapour saturation. The initial rapid gravity decline in Naglagbong from 1979 to 1984 was followed by minor gravity decreases from 1984 to 1990 due to declining local production and cold water influx. Mass recharge at Tiwi was estimated to be a minimum of 50% of net withdrawals between 1979 and 1990.

10.6 Larderello (Italy)

Larderello was the first geothermal field to be commercially exploited: production began in 1921. The field is vapour-dominated. Total production is currently about 800 t/hr (7 Mt/yr) of which about 200 t/hr (1.8 Mt/yr) is reinjected.

Microgravity surveys began in 1986, and since then a further 5 surveys have been made: 1987, 1988, 1989, 1991, 1993 (Dini et al., 1995). Gravity changes during the whole of this period have been very small. The largest changes have been similar to the "environmental noise" (15 microgal), indicating there has been almost complete mass recharge. Consistent, positive gravity changes in the main reinjection area, however, suggest that some of the reinjected water is being accumulated.

10.7 Travale-Radicondoli (Italy)

Travale field is located about 15 km southeast of Larderello. It is also a vapour-dominated geothermal system, and the average production rate is 100 kg/s (3.15 Mt/yr). Reinjection is insignificant.

Microgravity measurements were first made in 1979, and since then 7 further surveys have been made. Only small (<30 microgal) gravity changes have been measured. Analysis of the data shows about 97% of the fluid withdrawn between 1979 and 1991 has been replaced, indicating that (for this period of time) the field has been in a quasi-equilibrium state with respect to mass changes (di Filippo et al., 1995).

10.8 The Geysers (United States of America)

The Geysers is a vapour-dominated field, located in northern California, and is the largest field in the world both with respect to lateral extent and power produced. Production began in 1960 with an 11 MW plant and by 1993 the field was producing 1193 MW, however, since the late 1980s there has been considerable decline in the supply of steam. Information about the field has been restricted by commercial confidentiality, but Denlinger et al. (1981) state that between 1974 and 1981 about 20% of the mass withdrawn was reinjected, and the net mass produced was about 26 Mt/yr.

Microgravity measurements were made in 1974, and repeated in 1977. The maximum gravity change was -120 microgal, near the centre of the production region, and analysis suggested that recharge was small (Isherwood, 1977). The data was also analysed by Allis (1982) who showed that the ratio of gravity change to ground subsidence may be a useful indicator of the rate of fluid depletion in vapour-dominated systems because it was independent of reservoir thickness, pressure drop, and porosity. The ratio for that part of the field with greatest production was about -14 microgal/cm corresponding to a recharge of about 55%, but in some parts of the field the recharge was less than 25%. No published reports of gravity change measurements have been made after 1977, except for a brief (38 day) test of a cryogenic gravimeter in 1979 (Olson and Warburton, 1979). However, calculations (Allis et al., 2000) suggest that there will have been an average gravity decrease of up to 60 microgal/y, peaking about 1987, and the cumulative gravity change at The Geysers has been about 1000 microgal.

Recently, injection of water from outside the field has begun at several places in the field: the Southeast Geysers Effluent Pipeline project (SEGEP). Calculations (Allis et al., 2000) show that the gravity effects of this reinjection will be in the range 1-4 microgal year, and microgravity measurements may be useful in tracking the path of the injected water.

10.9 Cerro Prieto (Mexico)

Cerro Prieto is a liquid-dominated field situated in the north-western part of Mexico. Production began in 1973 with an output of about 69 MWe, which has been progressively increased to about 570 MWe in 1995.

Microgravity measurements of 70 survey points were started in 1978, and repeat surveys were made annually until 1983 (Grannell et al., 1984) but no significant results have been reported and it is believed the measurement programme ceased in 1983.

10.10 Hatchobaru (Japan)

Hatchobaru is a liquid-dominated field, situated in central Kyushu. A 55 MW power station was opened in June 1977 (No. 1 unit) and a further 55 MW added in June 1990 (No. 2 unit). The combined production rate is now about 1325 t/hr of liquid and 590 t/hr steam; there are 21 production and 10 reinjection wells in use. The main production is from depths of 1-2.5 km, and reinjection is at depths of 1-1.5 km.

Nineteen microgravity surveys, involving 44 survey points, have been made between 1990 and 1997 (Ehara et al., 1997; Nishijima et al., 2000). Gravity decreases of up to 250 microgal have been measured in the production area. In the reinjection area, gravity values at one point increased rapidly by up to about +80 microgal, and have since gradually decreased. Mass changes, calculated by integrating the gravity changes, suggest that between 1991 and 1993 of 32.4 Mt withdrawn, 16.7 Mt was discharged to the atmosphere, 15.7 was reinjected and about 16.3 Mt of natural recharge occurred (Nishijima et al., 2000).

10.11 Takigami (Japan)

Takigami is a liquid-dominated field, situated in Kyushu. A 25 MW power station began production in November 1996; there are 4 production and 9 reinjection wells.

Eleven microgravity surveys were conducted between May 1991 and March 1993 (Ehara et al., 1995); these surveys span a 4 month period of pre-production and reinjection testing (3 Mt withdrawn, 2 Mt reinjected) conducted between November 1991 and February 1992. Gravity changes of up to -150 microgal were measured, but most of the changes were found to be due to large seasonal variations in shallow groundwater level. Takigami lies in a mountainous area with an annual rainfall of 2.6 m, most of which occurs in the summer months. After correction for the gravity effects of these variations, gravity changes of up to +30 microgal were determined for the reinjection area and up to -40 microgals in the production area (Ehara et al., 1994, 1995).

Since then, efforts have concentrated on better determination of the correction for groundwater level changes using a multivariate regression model (Nishijima et al., 1999; Fujimitsu et al., 2000). A comparison between precipitation and gravity shows that there are phase lags of 3-8 months between rainfall and groundwater level changes. The accuracy of the gravity changes obtained after removal of the groundwater changes determined in this manner is estimated to be 10 microgal. Published data (Fujimitsu et al., 2000) show that in the production area there were gravity decreases of up to 30 microgal immediately prior to production (1995-1996), and increases of up to 40 microgal after production (1996-1997). There appears to have been no gravity changes in the reinjection area since production began.

10.12 Yanaizu-Nishiyama (Japan)

Yanaizu - Nishiyama is a liquid-dominated field, situated in central Honshu. A 65 MW power station was commissioned in May 1995. The production rate is 71 t/hr water and 525 t/hr steam from 15 deep wells (1.56-

2.70 km). There are 3 reinjection wells (1.5 km deep).

Microgravity measurements were started at 83 survey points in September 1994; annual surveys have been conducted since then and the survey network expanded to 138 points (Takemura et al., 2000). Since 1998, monitoring surveys have been carried out three times a year to determine if seasonal gravity variations occur. Near one gravity station, a weather monitoring station and soil moisture measuring equipment have been installed. At the weather station, barometric pressure, air temperature and rainfall are measured at 30 min. intervals. Shallow groundwater monitoring wells have been installed adjacent to 10 gravity survey points, and changes in water level monitored at 30 min. intervals.

11. LESSONS LEARNED

Microgravity measurements began at Wairakei geothermal field nearly 40 years ago, and since then the techniques of measurement and interpretation have been developed, and we have learned:

1. It is important that a good baseline data set is obtained before exploitation begins.

2. The gravity surveys need to be accompanied by surveys to monitor ground subsidence and groundwater level changes.

3. The measurement points need to extend well beyond the field boundaries to locate areas where reinjected fluid may be going, to determine the significance level of the measurements, and to check that gravity changes have not occurred at the base station.

4. The largest gravity changes occur in the early stages of exploitation and are associated with development of a two-phase zone: surveys at this time need to be more frequent.

5. The greatest benefits are achieved when the gravity change data are used in conjunction with numerical reservoir simulation models.

6. Predictions (of gravity change) are often wrong, and should be treated only as a rough guide to planning the microgravity surveys.

7. We have never regretted obtaining more (extra) microgravity data; we have often regretted not taking more. It is not possible to go back in time to collect extra data.

12. FUTURE TRENDS

Although the microgravity technique has been well developed over the last decade, some improvements can still be made. The following are suggestions of what can be done.

12.1 Determination of the effects of groundwater and soil moisture variations

At present few studies have been made of the gravity effects of changes in shallow groundwater level and changes in saturation in the Vadose zone. In porous formations, such as occur near the surface in active volcanic regions, variations of several metres can cause gravity changes of about 10 microgal/m of groundwater level change. Seasonal variations in water storage in the Vadose Zone are also likely to be important; changes of about 12 microgal have been recorded in Finland (Makinen and Tattari, 1991).

12.2 Improvements in measuring and determining the effects of ground subsidence

In some fields, such as Wairakei and Ohaaki, significant ground subsidence has occurred as a result of pressure drawdown in the reservoir and needs to be corrected for in determining gravity changes associated with mass variations in the reservoir.

Values for subsidence at the survey marks are usually obtained by optical levelling surveys; generally to 2nd order standard. This traditional technique is time-consuming and therefore costly. New techniques are emerging which may replace optical levelling; these include (differential) GPS surveys (Nunnari and Puglisi,1994) and Synthetic Aperture Radar interferometry (Massonnet et al., 1997). At present these methods cannot provide the required precision quicker than optical levelling, except in regions of high topographical relief and poor access, but it is anticipated that improvements will occur in the near future.

To obtain an accurate correction for the gravity effect of subsidence it is also necessary to know the vertical gravity gradient at each survey mark. For some microgravity surveys the standard theoretical "free air" correction value of -308.6 microgal/m has been used for all measurements, and in other surveys an average of several measured values has been used: -302 (±5) microgal/m for Wairakei and -295 (±8) microgal/m for Ohaaki. Further studies are needed to measure and incorporate local variations of gradient into the calculation of the gravity effects of subsidence, and so reduce the uncertainty in the gravity change values.

12.3 Borehole gravimetry

Currently, all microgravity surveys in geothermal fields have been made at the ground surface, but the amplitude of the measured gravity changes would be greater if the measurements could be made closer to, or within, the regions of mass change. This has been suggested for monitoring depletion of hydrocarbon reservoirs (Schultz, 1989), however the temperature in geothermal wells is much higher than in oil and gas wells. Some borehole gravimeters (BHGM) have been developed for use in the mining and petroleum industry (Robbins, 1989; Popta et al., 1990), but currently the maximum environment temperature limit for such instruments is about 260°C, they require a 7 inch diameter hole, which must not deviate more than 14° from the vertical. Improvements in temperature limitations and reduction in the size of the instrument would be required to make this technique feasible for geothermal field operation. In addition, a technique would need to be developed to ensure accurate repositioning of the meter in the hole in repeat surveys.

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