Environment BOP
Environmental Publication 2002/10
November 2002

Groundwater Resources of the Bay of Plenty

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Quay Street
P O Box 364
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NEW ZEALAND

ISSN 1175 - 9372

Foreward

This synopsis report summarises the current knowledge of groundwater resources in the Bay of Plenty and is based upon Chapter 15, Bay of Plenty Groundwater (Gordon 2001) Hydrological Society Publication “Groundwaters of New Zealand” edited by Michael R Rosen and Paul A White 2001.

Acknowledgements

I would like to thank Lorelle Mant at Environment Bay of Plenty for assistance with compiling diagrams for this report. I would also like to thank the Environment Bay of Plenty word processing team for their assistance with compiling this report and Ed Parks for editorial comments.

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1 Introduction

The Bay of Plenty region is located on the east coast of the North Island. The region extends from Waihi Beach in the northeast to Cape Runaway to the southwest and includes the catchments that flow into the Bay of Plenty (Figure 1). The land area of the region is 12 247 km^2 with a population of 243 078 (2001 census, provisional results) and has the third-fastest regional growth in New Zealand. Just over 60 % of the region population live within the cities of Tauranga and Rotorua.

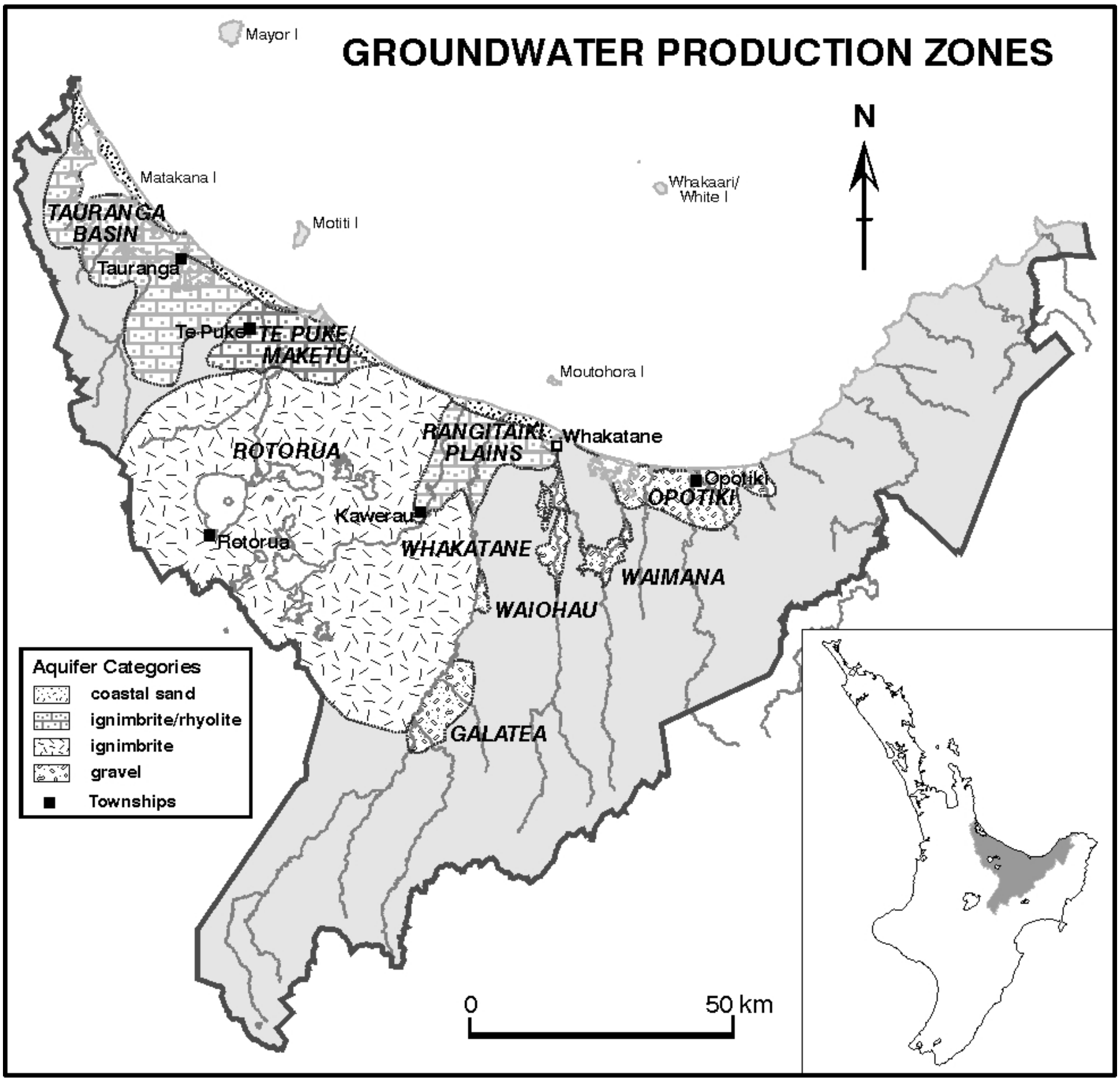


Figure 1 Groundwater production zones in the Bay of Plenty region

Groundwater in the Bay of Plenty is used for urban drinking water supplies, industry, agriculture and horticulture. Groundwater resource assessment began during the 1980s, at a time of high demand for water resources for irrigation and frost protection because of the expanding kiwifruit industry. Investigations were undertaken to determine the availability of groundwater and its suitability for kiwifruit irrigation and for public water supplies.

Groundwater is becoming an increasingly important resource, especially for irrigation, as demand for water in the region increases with regional economic growth and as surface resources approach full allocation.

The Bay of Plenty region also has a large number of geothermal systems, both low-temperature tectonic and high-temperature volcanic systems. Geothermal fields provide a cheap source of energy for industry, and communities of the region. Many geothermal fields within the region have associated surface features such as geysers and hot springs that are valued for their natural uniqueness, attracting visitors to the region. Geothermal activity is also traditionally valued for bathing and cooking uses.

2 Groundwater Resources

Groundwater resources of the region are predominantly found in the rhyolite ignimbrite deposits and volcanoclastic sediments in the Western Bay of Plenty, Tauranga and Rotorua areas. Highly productive ignimbrite aquifers are found on the Rangitaiki Plains in the Eastern Bay of Plenty. The source of these lithologies is the Taupo Volcanic and Coromandel Volcanic zones (Figure 2).

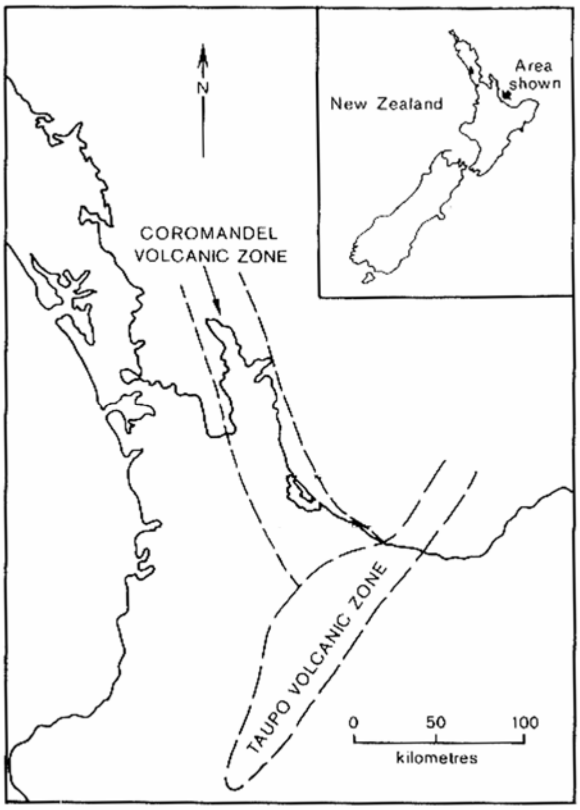


Figure 2 Location of the Quaternary Taupo Volcanic zones and Miocene Coromandel Volcanic zones (from Simpson and Stewart 1987)

Groundwater resources in the Eastern Bay of Plenty are mostly found in shallow alluvial gravel and pumiceous sand aquifers in the flood plains and river terraces of the Rangitaiki, Galatea, and Opotiki river catchments. There are also numerous shallow sand aquifers within paleo-dune systems along the coastal margins of the region.

The groundwater resources of the region are identified on the basis of production zones where bores have encountered groundwater in the volcanic or alluvial formations. In general aquifers are found within seven production zones (Figure 1): Tauranga basin, Te Puke-Maketu basin, Opotiki plain, Galatea plain, Coastal plain, Rangitaiki plain, and Rotorua volcanic plateau.

2.1 Tauranga Basin

The two main geomorphic features of the Tauranga area are the Kaimai Range and Tauranga basin. The Kaimai Range is a product of andesitic volcanism and consists of alternating lavas and breccias that define the western margin of the Quaternary Tauranga basin (Figure 3). The andesitic lavas dip eastwards, with possible down-faulting (Simpson and Stewart 1987).

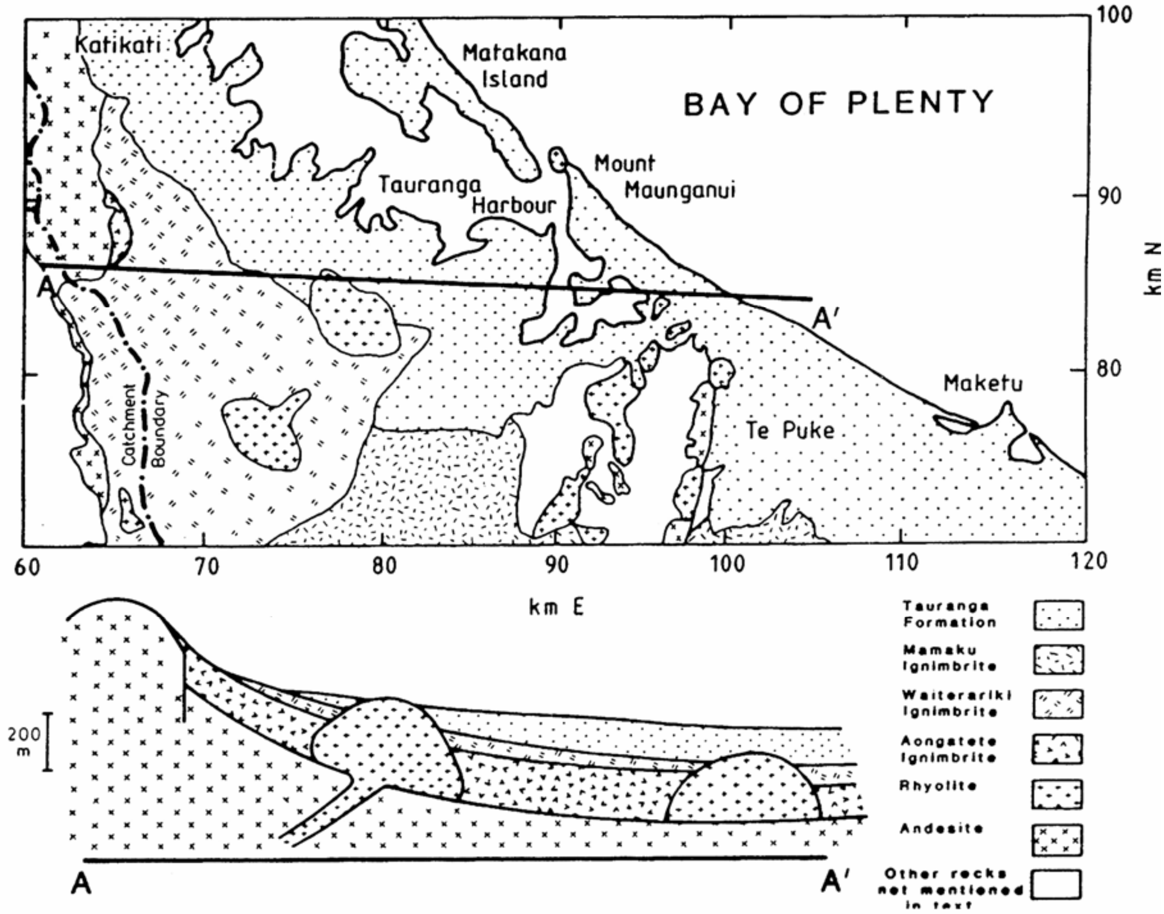


Figure 3 Surface geology of the Tauranga basin and cross section with the stratigraphic relationships (from Simpson and Stewart 1987).

The Tauranga basin contains volcanic rhyolite lavas and dacitic to rhyolitic ignimbrites and tephras derived from the southern Coromandel Volcanic Zone and the Taupo Volcanic Zone. The stratigraphic sequence consists of andesitic lavas overlain by dacitic and rhylitic ignimbrites known as the Aongatete and Waiteariki ignimbrite formations. These in turn are overlain by the sedimentary Tauranga Group Formation, consisting of series of silts, sands, gravels and intercalated rhyolitic ashes (Figure 3). Many of the volcanic units are the source of debris that has been reworked by fluvial processes and redeposited in sequences interbedded with the volcanic formations (Briggs et al. 1996). The landscape is dotted with a number of rhyolitic lava domes that have been extruded through the andesitic basement and are now exposed e.g. Mount Maunganui. Many buried rhyolitic lavas domes have also been encountered during drilling within the Tauranga basin.

Four general aquifer types are found in the Tauranga basin: ignimbrite aquifers, fractured rhyolite aquifers, sand and pumice aquifers, and gravel aquifers.

Isotopic and geochemical studies have confirmed that the Tauranga basin aquifers are recharged by rainfall from higher elevations within the Kaimai Ranges, albeit very slowly (Simpson and Stewart 1987), but additional recharge occurs between aquifers as a result of leakage from adjoining formations. Yields of 5 to 15 L/s are available in most of the Tauranga basin aquifers from correctly designed and constructed bores (Groundwater Consultants New Zealand Limited 1985a).

Low-transmissivity zones are often encountered in the Tauranga Basin Aquifers, within zones of unwelded ignimbrite, which can result in flow boundaries and large drawdown effects (Groundwater Consultants New Zealand Limited 1985a, 1985b). Fractured rhyolite aquifers have been found to produce yields of up to 75 L/s but the limited extend of these aquifers often restricts their use at higher pumping rates (Groundwater Consultants New Zealand Limited 1989, Woodward Clyde 1991).

2.1.1 Aongatete Ignimbrite Aquifer

The Aongatete Ignimbrite aquifer is the main source of cold water and low-temperature geothermal waters beneath the Tauranga basin. This predominately unwelded ignimbrite formation underlies much of the local basement over most of the Tauranga basin and is overlain by the welded Waiteariki Ignimbrite Formation and the Tauranga Formation (Skinner 1986; Houton and Cuthbertson 1989). The Aongatete aquifer is generally confined by the lower-permeability Tauranga Formation sediments. The aquifer extends over an area of approximately 800 km^2 at depths from 200-600 m with an aquifer thickness ranging from 290 m to 490 m, that dips eastward into the Tauranga basin (Skinner 1986). Many of the deep bores drilled into this unit contain warm water, with temperatures between 30°C and 55°C.

The aquifer has a transmissivity of 10-100 m^2/day and storativities of 2.5×10^{-4} to 4.5×10^{-4} (Groundwater Consultants New Zealand Limited 1985b). Bores generally have large drawdowns over short periods of time at low pumping rates. The aquifer has a relatively high storage coefficient, which indicates that the aquifer is receiving leakage from underlying or overlying units.

2.1.2 Waiteariki Ignimbrite Aquifer

The Waiteariki Ignimbrite aquifer is found within welded dacitic Waiteariki Ignimbrite Formation exposed in the eastern foothills of the Kaimai Range. The formation dips eastward toward Tauranga Harbour and uncomfortably overlies the Aongatete Ignimbrite aquifer; the top of the formation is non-welded and has been modified by erosion. The aquifer is at least 220 m thick, covering approximately 700 km^2 in the central Tauranga basin. Transmissivities typically range from 10 m^2/day to 100 m^2/day. Pump tests indicate that leakage occurs into and out of the Aongatete Ignimbrite aquifer. The aquifer is probably confined by the overlying low-permeability Tauranga Formation sediments.

2.1.3 Minden Rhyolite Aquifers

Numerous rhyolitic lava domes have been extruded through the andesitic basement within the Tauranga basin. Bores drilled into the rhyolite domes produce useful quantities of cold and warm groundwater as result of confined fracture flow through the domes. Cold groundwater is used for irrigation and in the Tauranga City area rhyolite aquifers produce warm water with temperatures ranging from 30°C to 55°C that is used for space heating and swimming pools. Cold and warm rhyolite aquifers are found at a reasonably shallow depths (120 m) but generally have a limited aerial extent (60 km^2).

The long-term sustainable yield of the ryholite aquifer systems is uncertain because recharge is currently unknown. Typically yields up to 75 L/s are possible, but pump testing suggests that safe yields of 20 L/s to 50 L/s are possible (Groundwater Consultants New Zealand Limited 1989; Woodward Clyde 1991). Transmissivities of 500 m^2/day to 1,400 m^2/day and storativities of 2×10^{-4} to 7×10^{-4} have been estimated for the ryholite aquifers in the Waihi-Athenree area (Groundwater Consultants New Zealand Limited 1989; Woodward Clyde 1991).

2.1.4 Western Bay Sand and Gravel Aquifers

Gravel and sand deposits found within the Tauranga Group sediments can produce water-bearing formations at depths of 30-150 m. Gravels are reasonably extensive in the foothills of the Katikati-Kauri Point area, but they do not appear to form extensive high-yielding aquifers. The gravels are often poorly sorted and contain a silt matrix that limits permeability. However, a number of boreholes drilled into discrete sand or gravel formation have encountered free-flowing conditions that produce sufficient yields (5 to 10 L/s) for useful domestic supplies (Groundwater Consultants New Zealand Limited 1985b).

3 Te Puke-Maketu Basin

Groundwater in the Te Puke-Maketu production zone is found within a fault-bounded basin that has been infilled with volcanic rhyolite lavas, dacitic to ryholitic ignimbrites and tephras from the Coromandel and Taupo Volcanic zones (Figure 4).

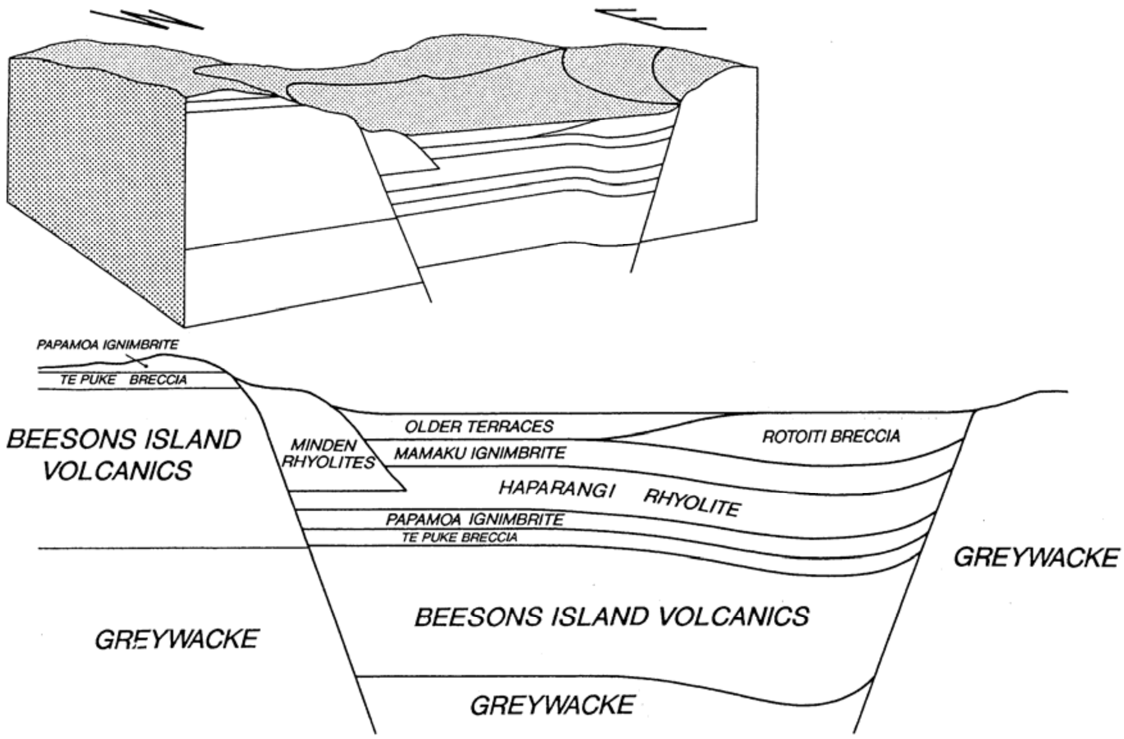


Figure 4 Geological structure and stratigraphic relationships of the Te Puke-Maketu basin (from Environment Bay of Plenty 1990)

Many of the volcanic units are the main source of debris and alluvium found in the basin. This volcanoclastic material has been reworked by fluvial processes and the redeposited in sequences that are often interbedded with the volcanic formations (Figure 5)(Environment Bay of Plenty 1990).

The aquifers in the Te Puke-Maketu groundwater production zone include shallow gravel, sands, pumiceous sands, pumice, hard fractured ignimbrites, and rhyolites. Shallow bores from 0 - 40 m depth generally intercept reworked alluvial gravels, sands, and pumiceous sands. Bores drilled from 60-140 m in-depth generally intercept ignimbrites and rhyolite. Bores drilled at greater than 140 m generally encounter warm groundwater. The fine-grained volcanogenic debris/alluvium appears to confine the shallow pumiceous sand aquifers and the deeper fractured ignimbrite aquifer.

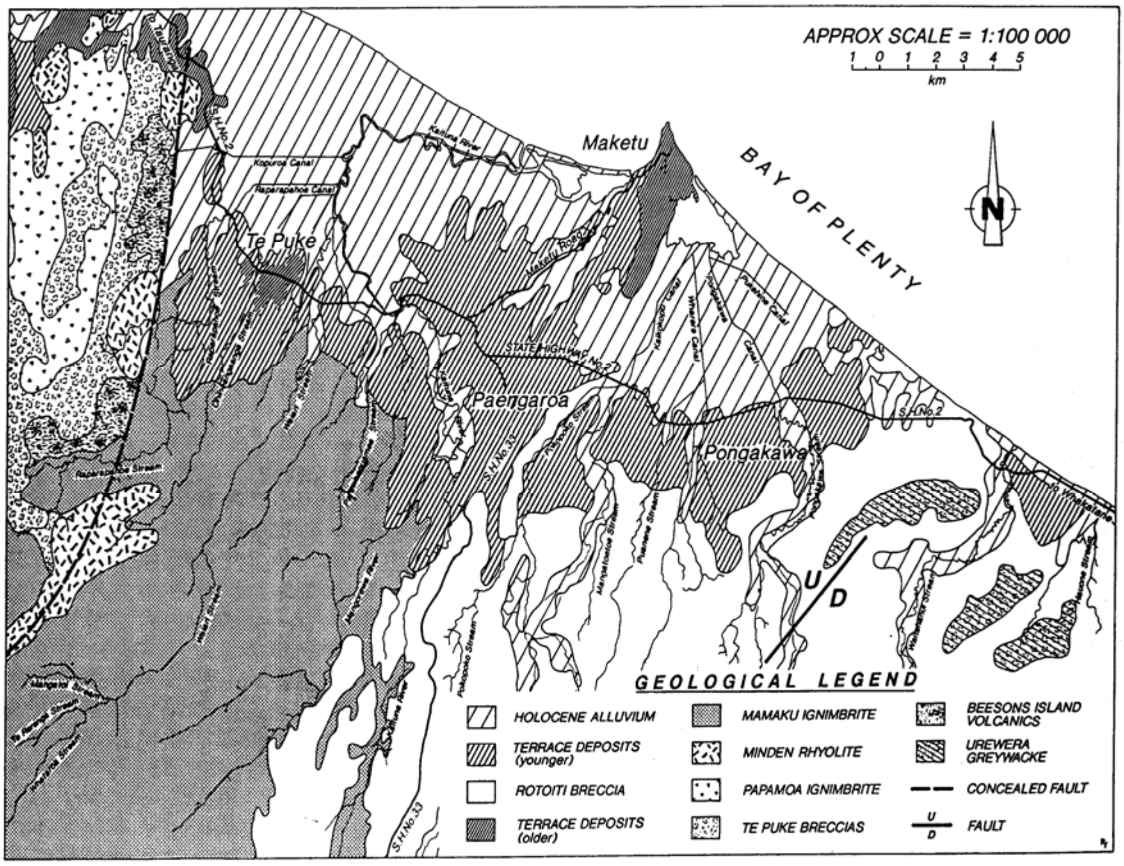


Figure 5 Geological of the Te Puke-Maketu basin (from Environment Bay of Plenty 1990)

To date no correlation has been made between geological formations and aquifers, but a conceptual geohydrological model shows the generalised groundwater flow within the Te Puke-Maketu basin (Figure 6.0). A major spring discharge zone correlates with the top of the Mamaku ignimbrite formation (Environment Bay of Plenty 1990). Bore water levels are found approximately 70 m below ground surface in inland areas. At the coast water levels are found at shallower depths, with some flowing artesian bores in the Maketu area.

Recharge is from direct rainfall infiltration inland at the head of the basin, from the Mamaku Plateau and Rotoehu Forest areas. West of Pongakawa, in the Rotoehu Forest, there are a number of blind valleys and streams where most of the stream flow is captured, directly recharging groundwater through fractures in the ignimbrite formations.

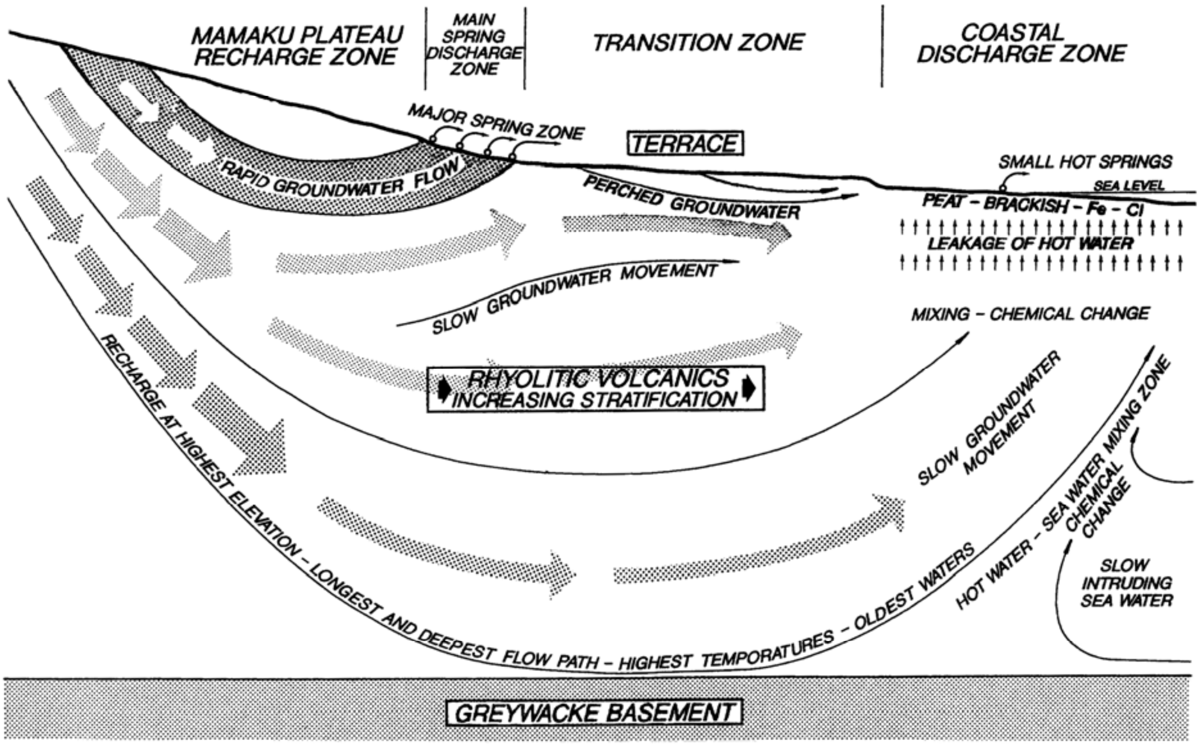


Figure 6. Conceptual geohydrological model of groundwater flow within the Te Puke-Maketu the basin

Yields of 2 to 12 L/s have been found from most aquifers in the Te Puke-Maketu basin and yields of up to 100 L/s are encountered in some deep bores. Higher yields tend to be from properly constructed bores in the deeper ignimbrite aquifers at depths of around 90-120 m. Transmissivity values in the deeper ignimbrite aquifers ranges from 350 m^2/day and 800 m^2/day with storativity values ranging from 2.5 x 10^{-4} to 7.5 x 10^{-4}, which is characteristic of fracture flow. Transmissivity values of up to 700 m^2/day have been measured in the shallow sands and pumice aquifers between 20m and 32m depth (Environment Bay of Plenty 1990).

4 Opotiki Plain

Groundwater occurs in the lower alluvial terraces of the Otara and Waioeka river valleys and within greywacke river gravels. Groundwater is used for municipal supplies, dairy sheds, stock water, and domestic supplies. The Opotiki plain has relatively high rainfall (1,400 mm mean annual rainfall), so the demand for groundwater for irrigation is low, however groundwater is used for kiwifruit and other horticultural crops during dry periods and for domestic supplies. Bore yields of up to 35 L/s have been encountered in adequately constructed bores drilled between 10 m and 70 m deep. Most bores have yields between 2 L/s and 10 L/s.

5 Galatea Plain

Groundwater is known to occur within gravel fan deposits on the Galatea Plain. The steep streams and rivers of the Ikawhenua range have transported eroded greywacke gravels and silts that have been deposited on Galatea Plain along with alluvial volcanic pumiceous sands from the Taupo volcanic zone.

Most bores that have been drilled on the Galatea Plain range between 10 m and 40 m in depth with generally low yields of 0.3 to 2.5 L/s, and occasionally yields of up to 5 L/s encountered. Several bores drilled to 60-80 m have encountered permeable water-bearing gravels with yields up to 20 L/s. Water-level monitoring of Galatea plain aquifer has shown that water levels vary from 6 m to 14 m below ground level, with shallower water levels generally occurring near streambeds.

Pump testing has shown that the gravel aquifers on the Galatea Plain are unconfined, with transmissivities up to 1,400 m^2/day and storage coefficients of 0.2 (Carrier & Associates Limited 1997). The permeability of gravel deposits on the Galatea plain is extremely variable and therefore there is some risk in drilling to greater depths to find high-yielding formations. However, zones of shallow higher-permeability gravel are often associated with streambeds. The flow of some streams is sometimes completely captured by the permeable gravels, and often emerges in the downstream streambed as springs.

Reported yield tests together with the analysis of bore logs indicates that the gravels on the Galatea plain have a high silt content that limits permeability. This is consistent with resistivity surveys that indicate low-permeability strata (Ministry of Works 1985). It is therefore likely that the gravel plain is too small and too close to the Ikawhenua Range source catchments for streams to form well-sorted permeable gravels (Pattle Delamore Partners 1996).

Groundwater is generally used for dairy sheds, stock water and domestic supplies, but there has been increasing demand for groundwater as a result of recent intensification of dairying demand which has resulted in demand for pasture irrigation to increase production during dry periods. The Galatea Plain groundwater resource is unproven for irrigation supplies and drilling to find high yields is considered to be speculative.

6 Coastal Plain

Groundwater is found at Waihi Beach, Matakana Island, Mount Maunganui-Papamoa Pukehina, and Ohope Spit in the paleo-dune systems. The sand aquifers are usually shallow and unconfined and are suitable only for local domestic supplies because of their limited extent and the threat of saline intrusion.

Many shallow groundwater bores are used for residential lawn and garden irrigation in coastal communities such as Mount Maunganui and Ohope. Most bores drilled in the sand aquifers along the coast are less than 10 m deep and have yields of 0.5 to 2.0 L/s. Water levels are generally 3 to 4 m below ground level. The sand aquifers are recharged by rainfall and often have poor water quality as a result of high iron and chloride. These aquifers are subject to contamination from land-use activities because they are generally unconfined.

7 Rangitaiki Plain

The Rangitaiki Plain is an alluvial coastal plain of over 300 km^2 of alluvial and marine sediments and paleo-dune systems (Environment Bay of Plenty 1991). The Tarawera, Rangitaiki and Whakatane rivers flow northwards over the plain. The elevation of the plain ranges from 30 m asl in the south to below sea level in the north. The northern area of the plain is cut off from the coast by a large dune system. Large areas of the northern plain are at, or slightly below sea level, and require substantial artificial drainage. This is controlled by a number of pumping schemes discharging groundwater to a network of canals.

The Rangitaiki Plain occupies the Whakatane Graben, that is an actively subsiding fault-bounded depression with a long-term subsidence rate of greater than 1.9 mm/year (Nairn and Beanland 1989). It is flanked to the west by the volcanic Kaharoa plateau and to the east by the greywacke basement rocks of the Raungaehe Ranges (Figure 7).

Volcanic ignimbrite, rhyolite and breccia deposits from Taupo volcanic zone outcrop to the south and west of the Rangitaiki plain. Greywacke basement can be found at depths of 1-2 km within the Whakatane Graben, which is infilled with alluvial and volcanic deposits (Figures 8a, 8b).

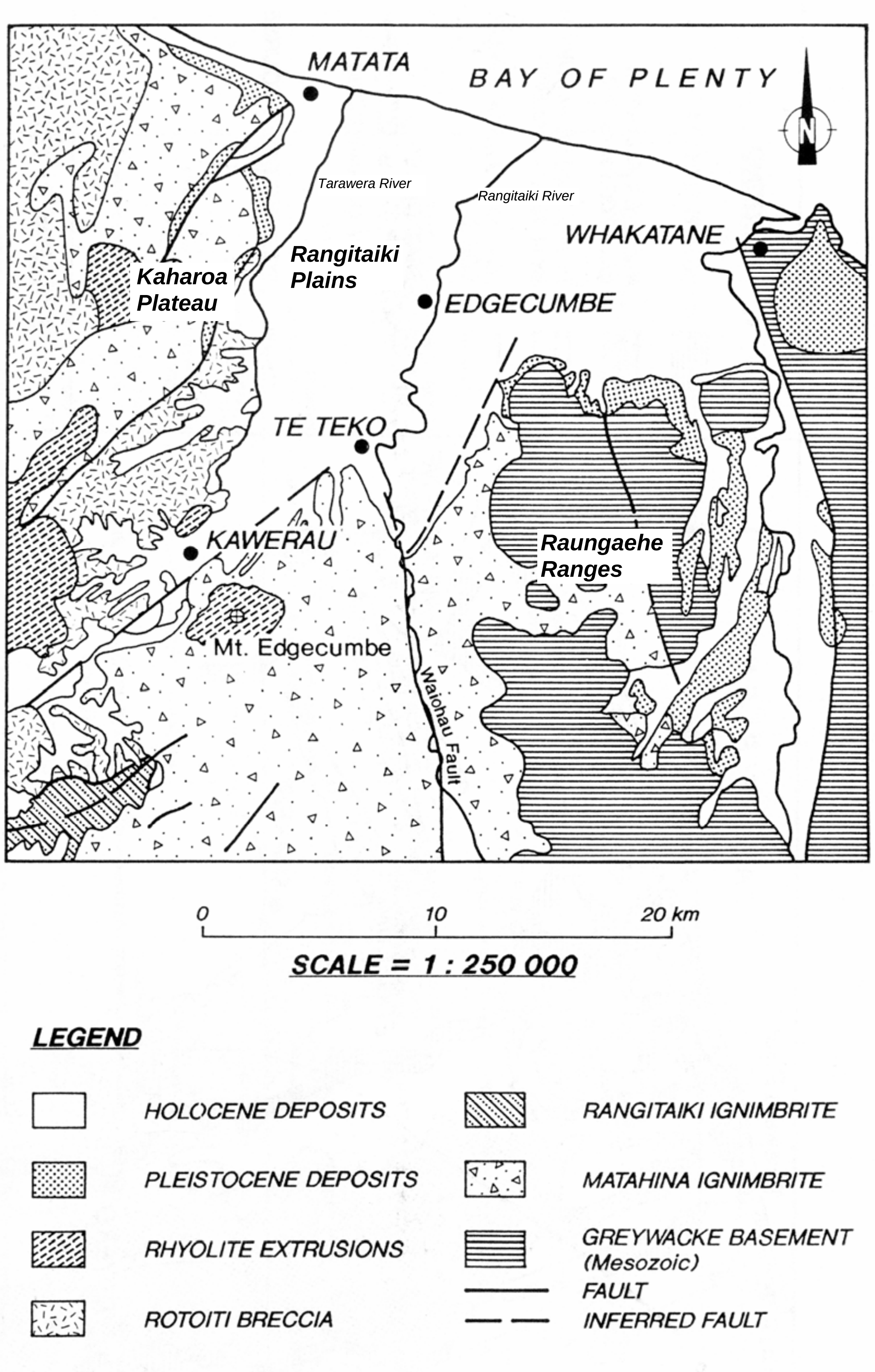


Figure 7 *Geology of the Rangitaiki Plains, Eastern Bay of Plenty (from Environment Bay of Plenty 1991).*

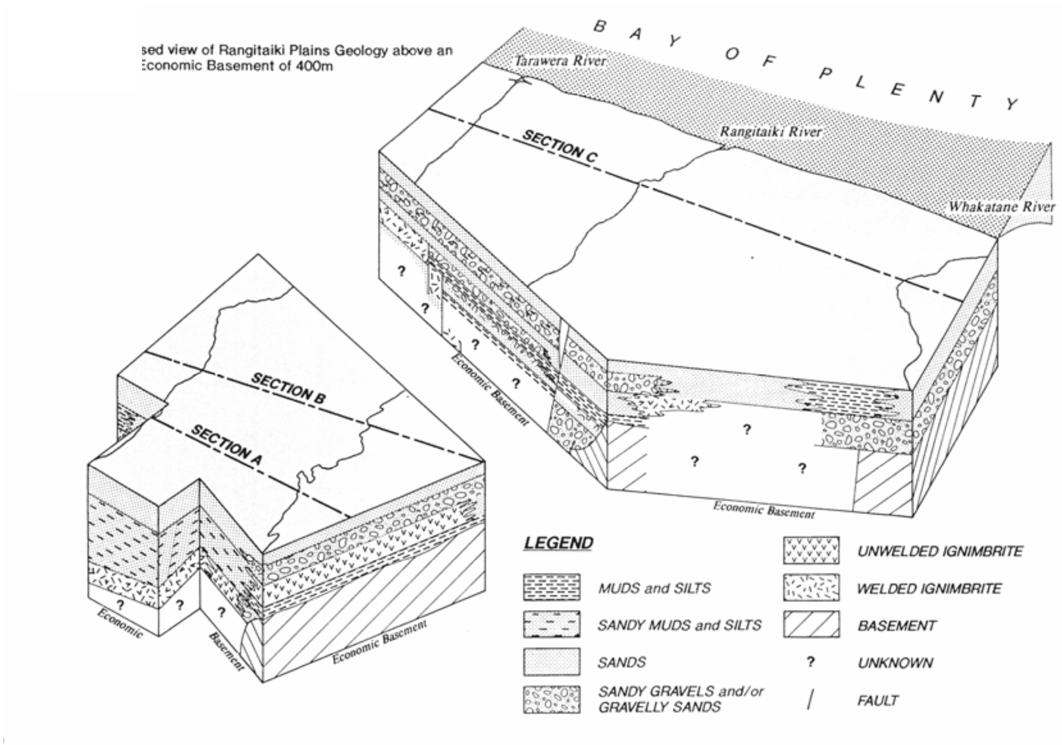


Figure 8a *Block diagram of the geology of the Rangitaiki Plains (from Environment Bay of Plenty 1991)*

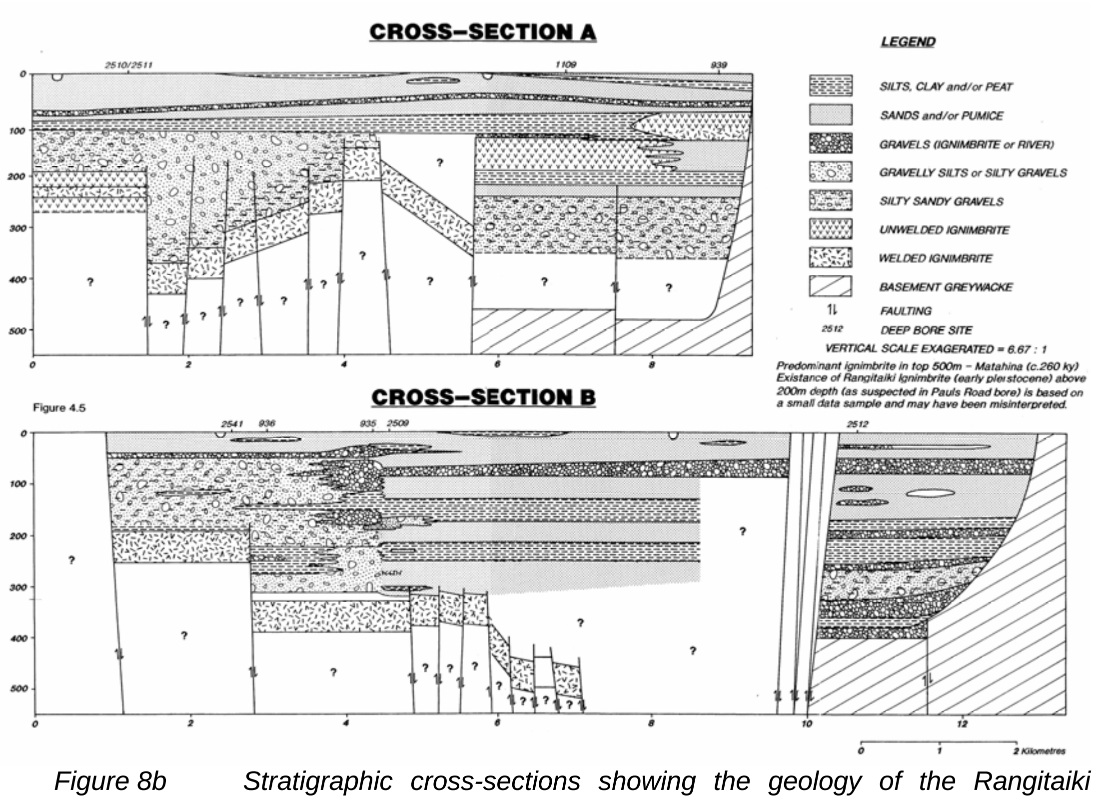


Figure 8b *Stratigraphic cross-sections showing the geology of the Rangitaiki Plains, complied from seismic profiles (Wood 1988, O'Connor 1990) and borelog stratigraphy (from Environment Bay of Plenty 1991)*

The Matahina Ignimbrite and the older Rangitaiki Ignimbrite have been identified beneath the Rangitaiki plains; these units are the product of major volcanic events within the Taupo Volcanic Zone. The likely source of the Matahina Ignimbrite is the Okataina volcanic centre, while the Rangitaiki Ignimbrite is thought to be derived from the Maroa volcanic centre, north of Taupo (Nairn 1999).

The shallow stratigraphy of the plain is dominated by unconsolidated alluvial sediments with alternating sequences of clay, peat, sand, pumice, and gravel (Figure 9). In the eastern plains the shallowest 10-15 m of sediment consists of alternating dune sands with peat. Elsewhere on the plains the shallowest 30 m of sediment consists of an alternating sequence of peat, silt and pumice that has been deposited by from the meandering river systems.

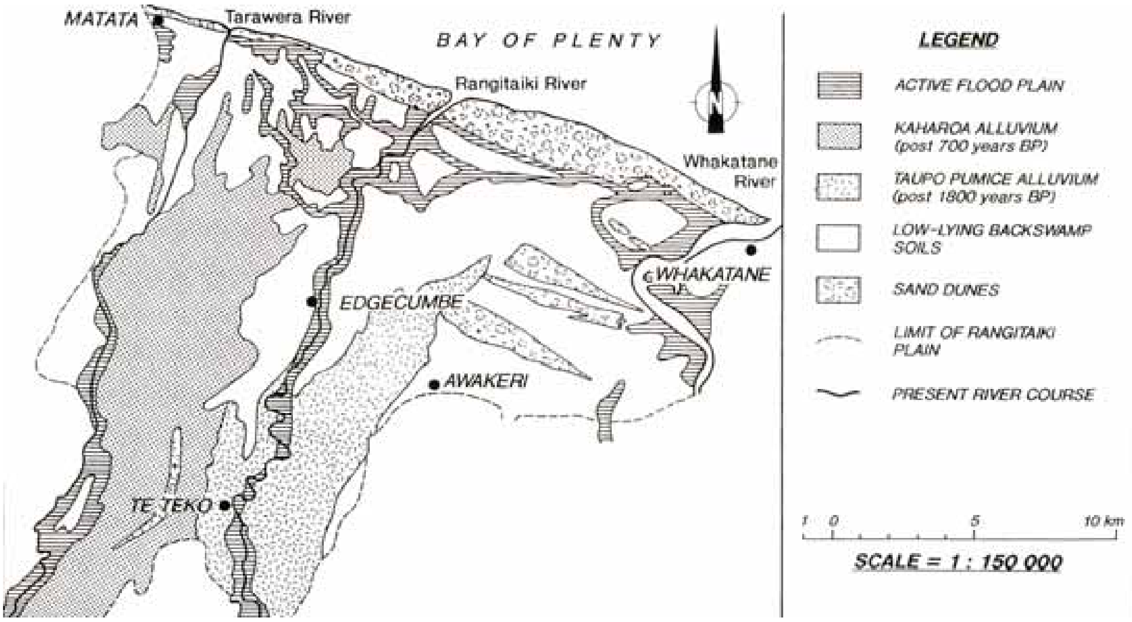


Figure 9 *Surface geology of the Rangitaiki Plains is dominated by alluvial material-peats, silt, pumice, sands gravels and dune sand deposits (from Environment Bay of Plenty 1991)*

The groundwater systems of the Rangitaiki plains is divided into a shallow system that is largely unconfined and extends up to 70 m deep, and a deeper groundwater system that extends to 400 m. The deep groundwater system becomes progressively confined with depth. The 400 m depth limit of deep groundwater system is considered to be the maximum that is economically feasible (Environment Bay of Plenty 1991).

7.1 Shallow aquifer system

The shallow aquifer system is mostly found in alluvial material. Shallow aquifers are found across most of the plains, but it is difficult to differentiate between aquifer systems because of the variable geology and limited understanding of the geohydrology. The shallow aquifers on the plain are generally unconfined or semi-confined by layers of peat, clay and silt.

Groundwater yields from the shallow aquifer systems vary considerably. The highest yields are found in cleaner sand and gravel horizons, with poor yields from silty sand, silt, clay and ash horizons. The average transmissivity is 445 m^2/day, but transmissivity values between 200 and 500 m^2/day are considered to be representative of the shallow aquifer system (Environment Bay of Plenty 1991).

Sources of recharge to the shallow aquifer systems includes; rainfall seepage from higher areas above the plains, and vertical leakage from the deeper aquifer systems. River gauging investigations have not shown any significant recharge of the shallow groundwater by rivers and surface drainage on the plain. Water level monitoring indicates that the shallow aquifer system responds to rainfall events. It has been estimated that between 15% and 30% of rainfall contributes to the shallow groundwater recharge on the plains (Environment Bay of Plenty 1991).

Shallow groundwater levels generally closely follow the topographic contours. Groundwater levels between Edgecumbe township and the coast are, to a significant extent, artificially controlled by a complex drainage system of pumping stations, floodgates and stopbanks. Numerous drainage schemes, pump water from the water table aquifers into canal systems, which then discharge to the major rivers. The groundwater level near coastal pump stations can fall to as much as 3 m below mean sea level as a result of pump scheme dewatering. Water levels in the shallow aquifers range from below mean sea level near the coast to between 11 and 13 m below ground surface at the head of the Tarawera and Rangitaiki River valleys, with annual changes typically ranging from 0.5 to 1.5 m.

Major springs are found on the periphery of the Rangitaiki plain, with Braemar and Jennings springs found on the western plain. Holland and Pumphouse springs are located on the southern Rangitaiki Plain near Kawerau (Figure 10). Both Braemar and Jennings springs supply the town of Edgecumbe and rural communities of the Whakatane District. On average Braemar spring discharges 259 L/s and Jennings spring discharges 44 L/s. Holland and Pumphouse springs supply Kawerau District communities and discharging 260 L/s and 90 L/s respectively. Pang (Environment Bay of Plenty 1994b) suggests that recharge for the springs is from the adjacent upland hill catchments.

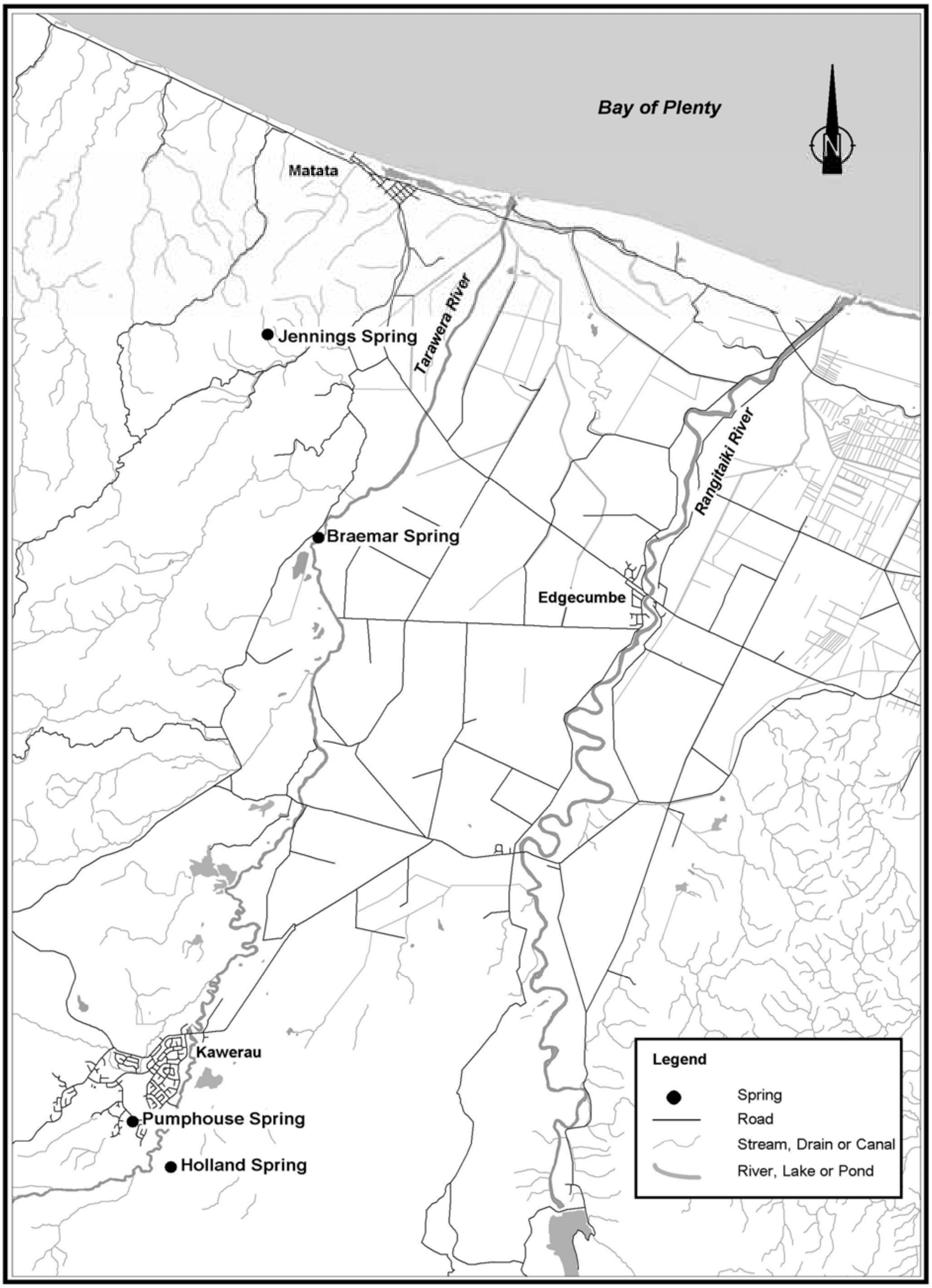


Figure 10 Location of the major freshwater springs of the Rangitaiki Plains.

7.2 Deep Aquifer System

The deep aquifer system, down to the economic basement of 400 m, is largely composed of unconsolidated alluvium, including; gravel, sand, pumice, ash/silt/peat horizons and hard rock volcanic ignimbrites. The ignimbrites tend to occur in the southwestern plain at Otakiri, although ignimbrite has been identified in the boreholes in the northern plain.

Geohydrological data for the deep aquifer system is incomplete because of the limited number of drill holes, and therefore it is not possible to correlate aquifers across the plain. A number of deep bores penetrate aquifer systems that contain unconsolidated volcanoclastic sediment. In the northeastern plain, and central and western plain lower bore yields occur because of lower permeability of the aquifer formations. In the southeastern plain pumiceous and greywacke gravels and sands form higher-producing aquifer systems (Environment Bay of Plenty 1991).

In the southwestern plain near Otakiri, pumiceous sands and gravels form part of a high yielding pressurised artesian system at depths greater than 100 m. The lower parts of this unconsolidated system may be the upper unwelded portion of the Matahina Ignimbrite formation. About 100 km^2 of the Matahina Ignimbrite is downfaulted within the Whakatane Graben between 120-300 m depth (Woodward 1988). This makes the Matahina Ignimbrite a significant aquifer resource on the Rangitaiki plain. The primary porosity is low, resulting in low yields, but yields are higher in the deeper, welded zones where water is stored and transmitted through fractures, cavities and joints (Environment Bay of Plenty 1991).

Transmissivity values for the deeper aquifers range from 18 to 6,000 m^2/day. Transmissivities in the unconsolidated pumiceous sand and gravel aquifers range from 200-900 m^2/day with an average of around 400 ml/day. In the southeastern plains, values up to 1,500 m^2/day are found. Transmissivities of 6,000 m^2/day to 12,000 m^2/day are found in fractured Matahina ignimbrite near Otakiri. The fractured ignimbrite can produce large volumes of water that is generally under artesian pressure with water levels up to 20 m above ground level on the western plain margin (Environment Bay of Plenty 1991).

Most deep bores show no “seasonal fluctuation” in water level and generally have an increasing head with depth. This suggests that the recharge source is beyond the plains. Deep recharge is likely to be occurring from volcanic formations in the west and south and also from transmission at depth from the upper river catchment alluvium. Oxygen-18 isotope results indicate a widespread rainfall source at an altitude of 100 m. Tritium and oxygen isotope analysis of samples from deep bores at Otakiri and Braemar Springs indicate that the mean residence time of the deep groundwater is about 50-100 years. Tritium results also indicate that the total storage volume of the Braemar Springs is around 6.3 million m^3, at least 50 times the annual discharge (Environment Bay of Plenty 1991). Recharge of the deep groundwater in the eastern plain is probably from seepage through transmissive materials underlying the upper Rangitaiki River valley.

Considerable uncertainty exists as to the discharge mechanism for the deep groundwater on the plains. No bores greater than 100 m exist along the coast, but the horizontally stratified nature of the sediments and a projection of the gradient of the deep Otakiri system suggest a discharge point off the coast (Environment Bay of Plenty 1991).

7.3 Rotorua Volcanic Plateau

The Mamaku Ignimbrite is the most significant geological formation containing groundwater resources in the Rotorua area. The ignimbrite was erupted from the centre of present Lake Rotorua, approximately 220,000-230,000 years BP. The Lake now occupies a large part of the caldera that resulted from the subsidence following the ignimbrite eruption (Houghton et al. 1995). The ignimbrite extends over an 100 km^2 area, is 120 m thick, and is composed of two discrete units. The lower unit of Mamaku Ignimbrite is strongly welded and highly fractured, where as the upper units are increasingly friable towards the top, with associated increases in porosity, and permeability. The high porosity in the upper units is a result of vapour phase alteration by hot gas streaming through the ignimbrite sheet soon after emplacement (Rosen et al. 1998). Numerous rhyolitic lavas and domes were also extruded through this ignimbrite. Later volcanic eruptions (late Quaternary) from neighbouring volcanic centres, deposited loosely compacted pyroclastic pumice, breccias and tephras of varying thickness (up to 30 m), which, have often been reworked by fluvial processes.

Most bores in the Rotorua area are drilled to 40-80 m in depth, into ignimbrite and rhyolite aquifers. Bores on the Mamaku plateau are generally drilled to 100 m depth into ignimbrite formations. The extensively fractured rhyolite and ignimbrite aquifers have low to moderate bore yields but are the source of numerous highly productive springs (Pang et al. 1996).

Six of the identified springs (Figure 11) in the Rotorua area are used for public water supply by the Rotorua District Council. Almost all the identified springs have flow rates greater than 20 L/s, with the highest producing springs in the Mamaku Ignimbrite (Rotorua District Council 1993).

The upland plateaus are the recharges areas for the ignimbrite and ryholite aquifers, and the lakes and rivers are discharge areas. The top unwelded zone of the Mamaku Ignimbrite contains uncompacted friable pumice that is very permeable and allows movement of water downward into joints within the ignimbrite formation. Surface water can enter these large depressions or “sink” holes that can be 10-30m deep and 3m across. Rapid surface water recharge to the aquifers through these depressions and holes occurs during heavy rainfall events. At depth, the joints form permeable flow paths for horizontal groundwater flow, with welded and unwelded zones often functioning as preferential flows paths. Water can perch on the welded zones and flow down through unwelded zones along the dip direction of the ignimbrite formation to emerge as springs (Rosen et al. 1998).

The large lakes of Rotorua and Tarawera are the main discharge zones for groundwater in the Rotorua area. The small lakes of Rotoma, Okareka and Rotokakahi discharge areas for local groundwater and also act as recharging lakes, through part or all of the lake bed, to other lakes in the area (Pang et al. *1996).* Lakes Rotoehu, Okataina, Tikitapu and Rerewhaaitu have no surface outlets and are therefore likely to recharge the regional groundwater.

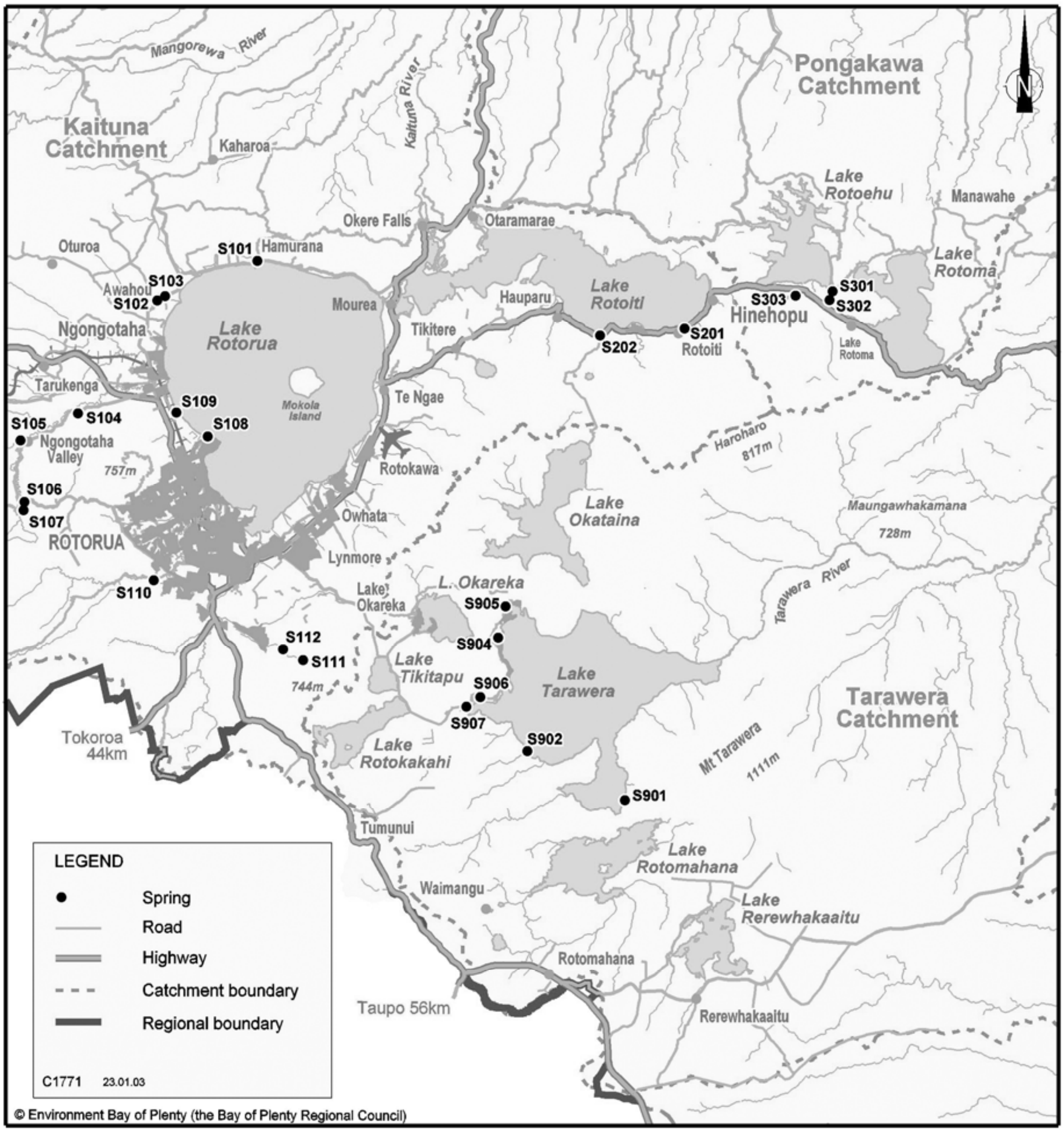


Figure 11 Cold water springs of the Rotorua groundwater production zone (adapted from Pang et al. 1996)

8 Groundwater Quality

The water quality of Bay of Plenty groundwater is generally good, but many bores have elevated levels of iron, manganese, arsenic, boron, nitrate and bacteria. A survey of arsenic levels in municipal supplies showed elevated levels of arsenic in groundwater supplies at Waihi beach, Rotorua, and Rangitaiki Plains. The high arsenic is likely to be derived from geothermal activity.

Bay of Plenty groundwaters are dominated by bicarbonate anions; high iron and manganese levels which are generally found in the region's shallow aquifers and can also occur in the deeper aquifers. High silica content is also common in Bay of Plenty groundwaters because of the relatively high abundance of silicate minerals in the volcanic rhyolitic pumice and ignimbrite formations. The high silica content is considered to be the source of high alkalinity values. Waters from the ignimbrite aquifers are generally aggressive, with pH values between 6 and 6.5.

The Tauranga basin ignimbrite and rhyolite aquifers have good water quality, apart from moderate iron concentrations, and the water is generally suitable for horticultural irrigation and domestic uses. Groundwater in the Te Puke-Maketu basin is moderately corrosive, with some bores having elevated iron levels, especially at Paengaroa. Groundwater is generally suitable for horticultural irrigation and stockwater. Some bores near Maketu and other coastal areas area have elevated chloride from seawater that has been trapped within aquifer sediments. Elevated nitrate levels have been found in the shallow groundwater in the Te Puke-Maketu area but nitrate levels tend to be below the drinking water standard of 11.3 mg/L nitrate nitrogen (Environment Bay of Plenty 2002). The source of the elevated nitrate is from intensive agriculture and horticultural land use activity in the Te Puke-Maketu area (Environment Bay of Plenty 2002).

Shallow groundwater on the Rangitaiki Plain contains higher concentrations of iron than the deep groundwaters. The shallow groundwater of the plains is dominated by sodium and bicarbonate water types that are typical of what would be expected in a shallow unconfined system *(Environment Bay of Plenty 1991).* However, water quality is variable because of high levels of iron and boron, but there are no geochemistry indicators that would suggest a geothermal input for the boron. The source of the high iron and boron is considered to be from layers of peat and organic material in the aquifer sediments. This has been confirmed from the high concentrations of boron found in peat deposits, particularly where peat has formed in saline or estuarine conditions (Kear and Ross *1961).* The areas with the highest concentrations of iron (Figure 13*)* and boron (Figure 14) coincide with the largest peat deposits found in the central and northern plains, between the towns of Edgecumbe and Thornton.

Shallow groundwater aquifers in the central plain do not meet iron and boron guidelines for potable, irrigation, and boiler feed water. High iron and manganese causes staining of plumbing fixtures and laundry and can accumulate in pipe work. Also high iron can causes blockages to irrigation lines and boron is harmful to some sensitive crops such as kiwifruit. The low alkalinity, pH and total dissolved solids of the shallow groundwater also make it unsuitable for boiler-feed water.

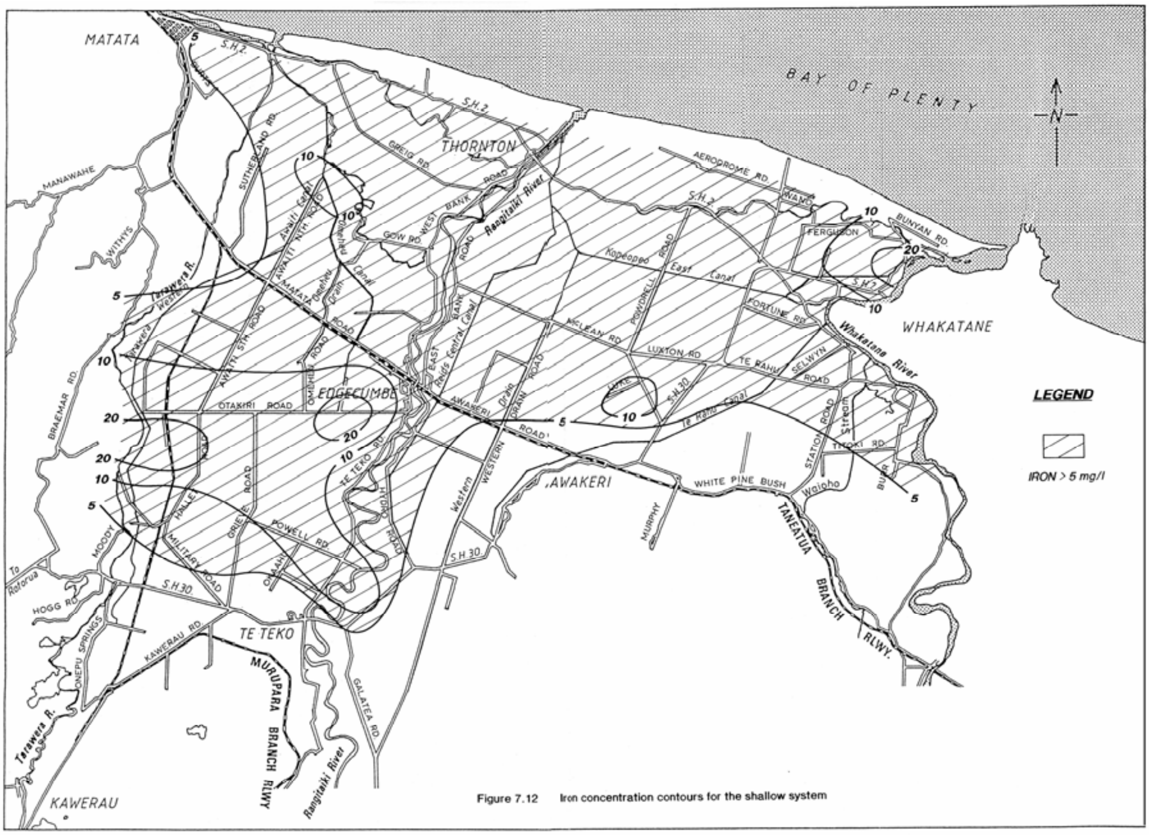


Figure 13 Contour map of iron concentrations in the shallow groundwater aquifers of the Rangitaiki Plains (from Environment Bay of Plenty 1991)

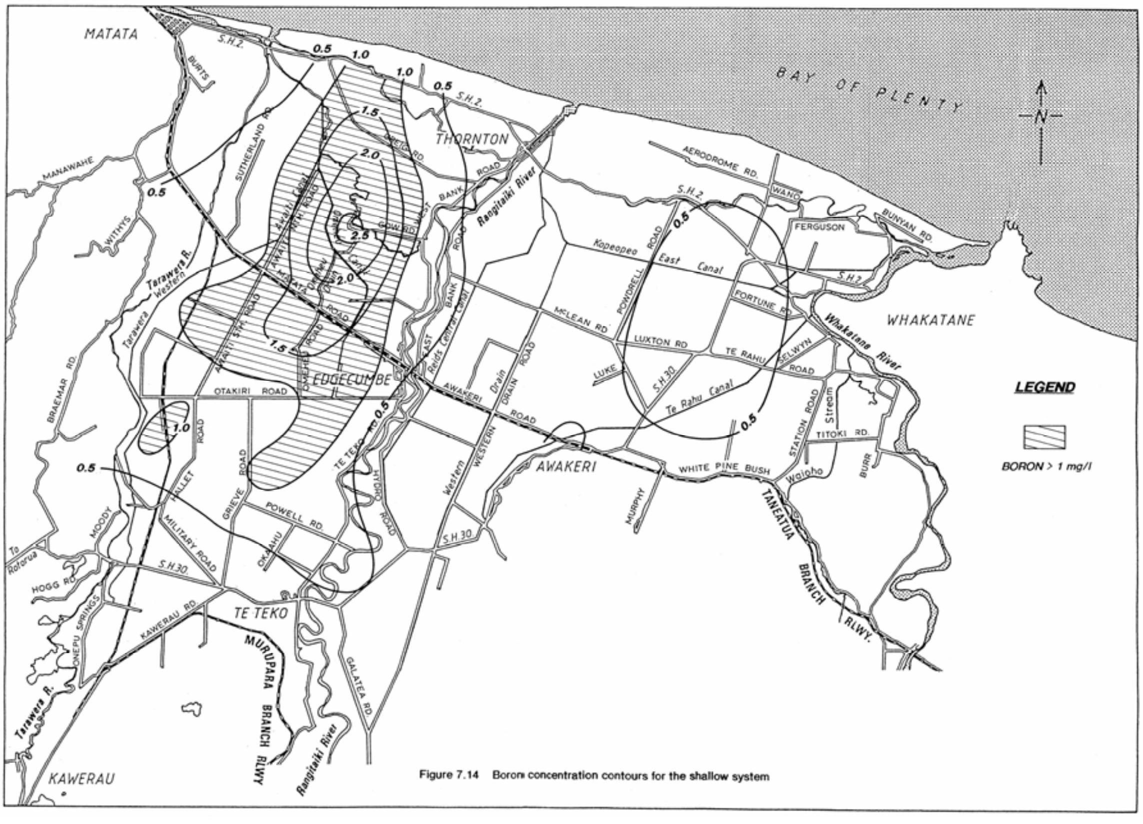


Figure 14 Contour map of boron concentrations in the shallow groundwater aquifers of the Rangitaiki Plains (from Environment Bay of Plenty 1991)

Nitrate is elevated in the shallow groundwater, on the plains, but nitrate levels are generally below drinking water guidelines. The source of the elevated nitrate is from intensive agriculture and horticultural land use activity on the plains Environment Bay of Plenty 2002).

The water quality of the Rangitaiki plain deep ignimbrite aquifers is generally very good and the water is widely used for irrigation and potable supplies. Deep groundwater is used for public water supplies with minimal treatment because of its generally high quality. This is because the recharge area for the deep groundwater area is likely to be beyond the plains, away from the effects of intensive horticulture and agriculture. Deep groundwater is typically, very soft because of the low total dissolved solids, and slightly acidic. Consequently, the water from the deep system is therefore corrosive to metallic pipe work or reticulation. Therefore corrosion resistant materials for bore construction is desirable. The deep groundwater also has a moderate to high silica content, which can cause scale problems in hot water or boiler systems. High iron concentrations occur in some deep bores that penetrate alluvial aquifers.

High arsenic levels (8 µg/L) have been found in deep municipal water supply bores that penetrate the ignimbrite aquifers at Otakiri (Davies et al. 1994). High arsenic levels have also been found in the Braemar and Pumphouse springs, which are municipal water supplies for the Whakatane rural community and the Kawerau township, but drinking water guidelines for arsenic are exceeded only in the Braemar Spring waters (Davies et al. 1994). The nearby Kawerau geothermal field is considered to be the source of the arsenic found in the Pump-house spring.

The water quality of ignimbrite and rhyolite aquifers in Rotorua is good and generally complies with potable water quality guidelines. However water from the ignimbrite aquifers is characteristically very soft (low total dissolved solids) and is slightly acidic, which makes the water moderately aggressive and corrosive to metallic pipe work. Groundwater that is used for public water supplies is usually treated to reduce the aggressive and corrosive effects.

9 Groundwater Use and Management

9.1 Ground Use

Environment Bay of Plenty requires water permits for any groundwater abstractions of over 15m^3/day. Over 75% of permits issued by Environment Bay of Plenty are within the Tauranga and Western Bay of Plenty districts (Figure 15), and over 83% of all permits are for horticultural irrigation (Figure 16).

Groundwater in the Tauranga basin is extensively used for horticultural irrigation and also for domestic and stock water supplies. The warm groundwater found in the Tauranga basin is used for private spas, public swimming pools, and for domestic home heating and commercial greenhouse heating.

The shallow aquifer resources on the Rangitaiki plains are extensively used for domestic and stock water. The deep groundwater is mostly used for horticultural irrigation and municipal water supplies. Groundwater fed springs supply the city of Rotorua and the small communities around Lake Rotorua. Springs also supply the rural towns and communities on the Rangitaiki plains. The Holland and Pump house springs supply communities in the Kawerau District and the Braemar and Jennings springs supply the town of Edgecumbe and rural communities in the Whakatane District.

Figure 15 Percentage of groundwater permits by district in the Bay of Plenty region.

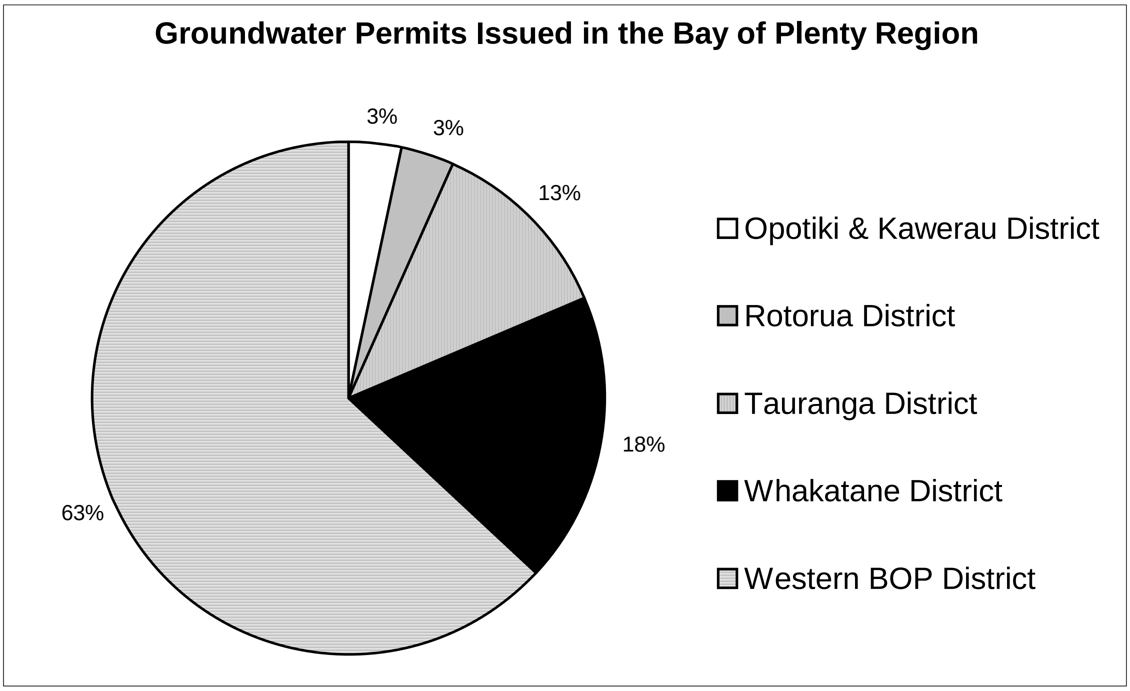
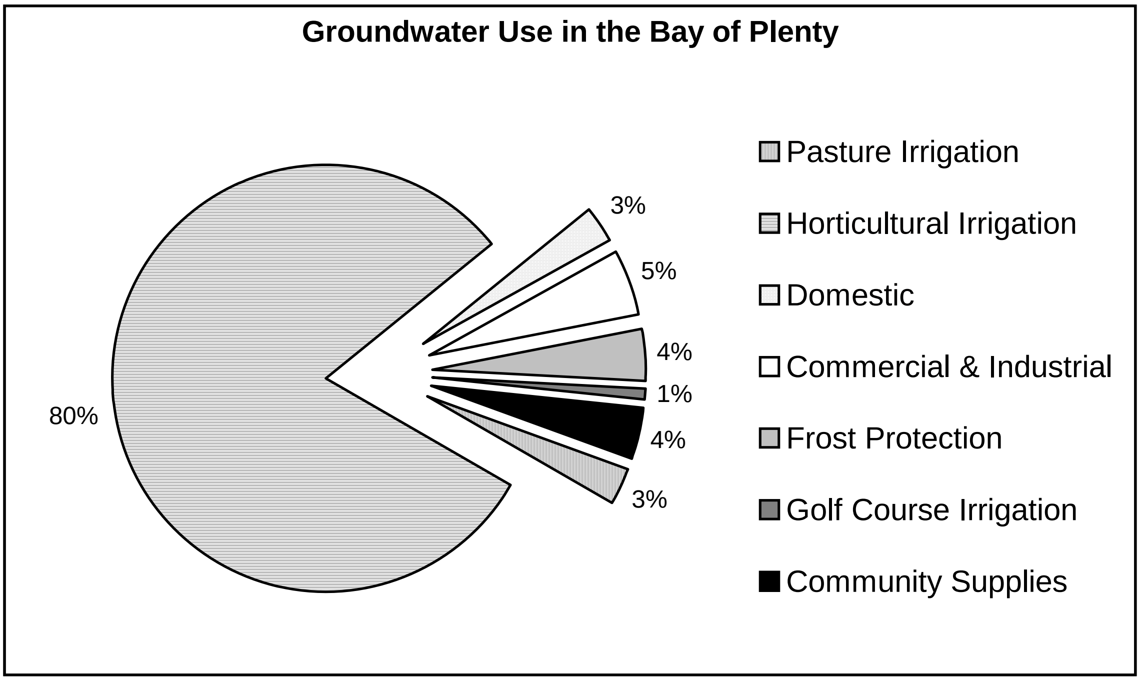


Figure 16 Groundwater use in the Bay of Plenty region as of December 2000



Groundwater in the Te Puke-Maketu area is used for irrigation, dairy shed and stock water, and provides potable water supplies to small rural communities.

The large increase in groundwater allocation across the region (Figure 17) in the early to mid 1980s, reflects the water demand for irrigation and frost protection for the large number of kiwifruit orchards planted at that time. Water demand peaked at 275,000 m^3/day in 1988, with subsequent reduction in the number of permits until the mid 1990s, when allocation stabilised at 220,000 m^3/day.

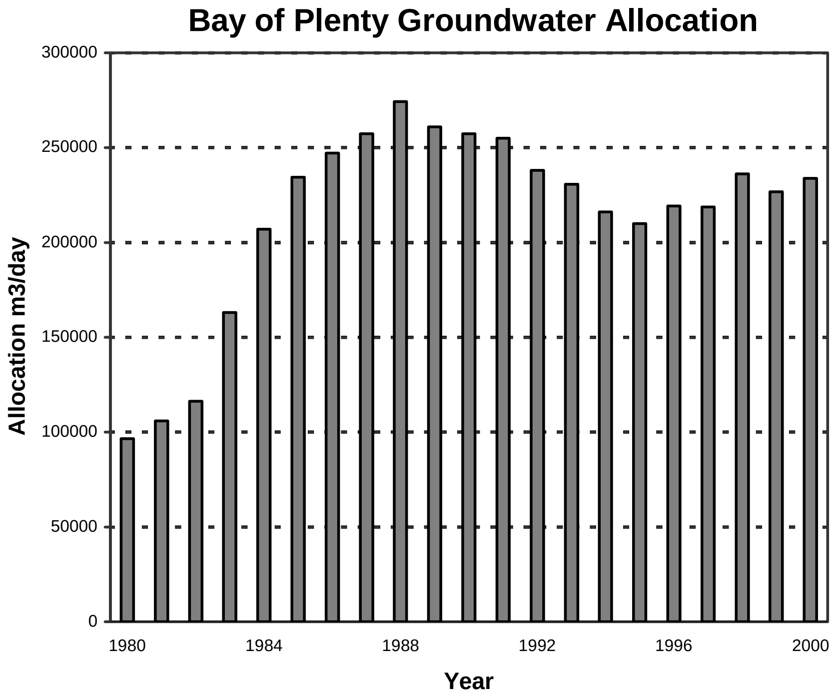


Figure 17 Allocation of groundwater in the Bay of Plenty region to December 2000

Since 1998 there has been an increasing demand for groundwater for pasture and horticultural irrigation. This is because of increased returns from dairy farming making it more economic to irrigate pasture during summer periods, and increased returns and water demands for the new varieties of kiwifruit. Demand for groundwater has also increased in the Western Bay of Plenty and in particularly in the Te Puke-Maketu area because changes in land use from agriculture to horticulture. It is also expected that further demand for groundwater in some areas will increase as surface water streams become fully allocated.

9.2 Groundwater Management

Groundwater use in the Bay of Plenty is currently allocated on a "first-come-first-served" basis and assessed case-by-case. At present, permit holders in the region are allocated a maximum quantity per day. Environment Bay of Plenty is currently working on a Regional Water and Land Resource Management Plan that will include policy, methods, and rules for the management of groundwater resources, and will provide for the allocation of groundwater at sustainable yields to ensure quality and quantity are maintained. Environment Bay of Plenty also monitors water quality and water levels to ensure aquifers are being managed sustainably.

10 Geothermal Resources

The Bay of Plenty region has a large number of geothermal systems (Figure 18), with both low temperature tectonic systems and high-temperature volcanic systems as classified by Hunt and Bibby (1982). Low temperature tectonic geothermal systems are commonly associated with faults and fractures into basement rocks. Meteoric water circulates at depth, and is heated by conductive or convective heat flow and then rises to the surface through faults and fractures to the ground surface. High temperature volcanic geothermal systems of the Bay of Plenty are found within Taupo Volcanic Zone and are often associated with active volcanism.

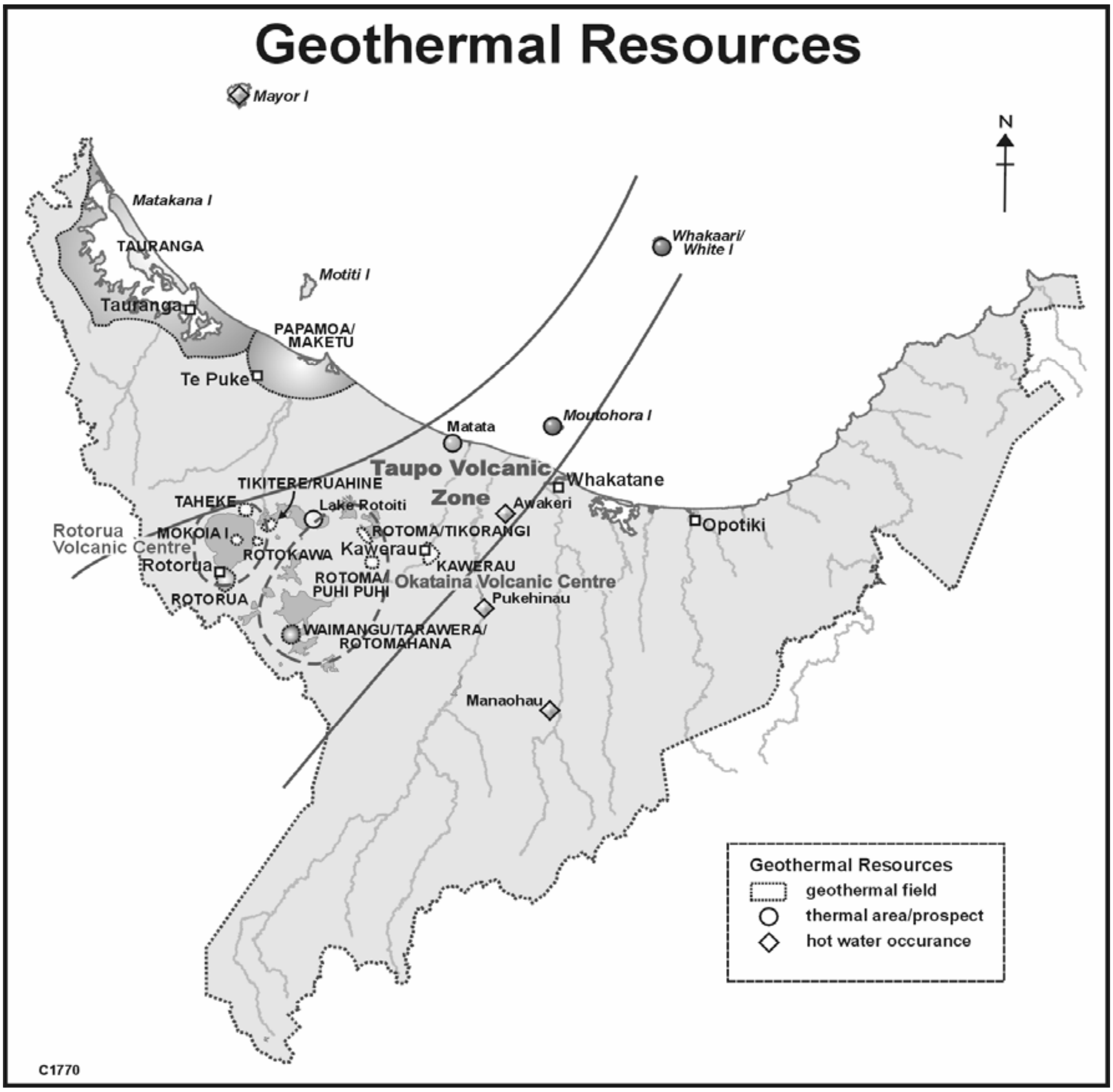


Figure 18 Geothermal resources of the Bay of Plenty region as of December 2000

10.1 Low-temperature tectonic geothermal systems

Warm groundwater is found near Maketu and around Tauranga harbour forming the Tauranga Te Puke-Maketu geothermal fields. Warm groundwater production is located within the Aongatete ignimbrite and Minden rhyolite domes. Warm groundwater is sourced from the fractures and joints in the rhyolite and ignimbrites. Bores that penetrate the resource have water temperatures ranging from 20°C to 55°C from bores

200 m to 600 m in depth. Production rates of 2.5 L/s can usually be expected from 100 mm bores (Environment Bay of Plenty 1994). Within the Te Puke-Maketu area of the field the Mamaku ignimbrite is the main warm groundwater source rock (Simpson and Stewart 1987). Near Maketu there are natural warm(40 - 45°C) springs and warm water can be produce from relatively shallow (40 - 60 m) artesian bores. This suggests that there is very high vertical permeability within the aquifer. Bores in the Te Puke area encounter the warm water at depths greater than 300 m.

Simpson (1987) suggested that the heat flow for the Tauranga and Te Puke- Maketu fields is a result of convective and conductive heat transfer associated with deep circulation of waters. Geochemistry, isotopic ratios and dating of groundwater (Simpson and Stewart 1987) indicates that the groundwater is hundreds of years old, with younger waters found to the west. This suggests that recharge is from high elevations and that water is circulating depth within the rhyolite and ignimbrites and then rising through faults and joints at the coast. The water geochemistry is predominantly bicarbonate and is weakly mineralised, but bores near the coast (particularly on the Mount Maunganui Peninsula) have a seawater signature, indicating seawater intrusion.

Warm groundwater from the Tauranga and Te Puke-Maketu field is generally used as a direct heat source for glasshouse heating, swimming pools, and private spas. A number of commercial operators use the warm groundwater for hot pools and swimming baths, for example, Sapphire Springs hot pools near Katikati, Fernland Spa hot pools, Welcome Bay hot pools and Mount Maunganui hot pools. Warm groundwater is also used for horticultural irrigation and frost protection. There are also many private bores throughout the Tauranga area that use warm groundwater for spas, swimming pools, and home space heating.

At Awakeri there are three hot springs, which are known as the Pukaahu hot springs. Two of the springs are natural and one was created by excavation. The temperature of these springs ranges from 58°C to 70°C and the heat output from the two original springs is approximately 0.4 MW. The hot water is neutral chloride-bicarbonate and is weakly mineralised. Six production bores have been drilled to 98m depth. These bores produce an artesian flow of approximately 50 L/s. Both the springs and bores supply hot mineralised water for the swimming pool complex. The discharge from the original springs has declined since the production bores have been in use (Mongillo and Clelland 1984).

The Resource Management Act differentiates geothermal water from groundwater on the basis of temperature (greater than 30°C). At present all abstractions of warm groundwater over 30°C in the Bay of Plenty region require a resource consent. Recently there has been an increased demand for warm water from the Tauranga field. In 1996 there were approximately 50 warm water groundwater bores with current consents, but as of November 1999 this had increased to 134 consented bores.

10.2 High-temperature Volcanic Geothermal Systems

There are thirteen known volcanic geothermal systems in the Bay of Plenty region, of which eight are high temperature fields; Kawerau, Rotorua, Rotokawa/Mokoia Island, Rotoma/Tikorangi, Rotoma/Puhipuhi, Taheke, Tikitere, and Waimungu/Rotomahana.

The level of information on individual geothermal systems varies greatly but temperature and field area has been defined (Table 1.1). The greatest amount of information is available for Kawerau and Rotorua. These fields have operational computer models, which reflects the high commercial value of the fields. Other geothermal systems have limited information but are recognised on the basis of surface activity (e.g. hot springs) and from resistivity anomalies.

Most of the volcanic geothermal fields in the Bay of Plenty region have unique surface features such as geysers, hot springs, hot pools, bubbling mud pools, deposits of silica sinter and sulphur, steaming ground, and a varied and unique ecology. The extent of some of the major volcanic geothermal fields in the Bay of Plenty region has been established from geophysical and geochemistry exploration of geothermal fields in the region (Cave et al. 1993; Keewood 1991; Allis et al. 1993).

Table 1.1 Major geothermal fields in Bay of Plenty region after Ministry of Commerce (1993)

Field	Approximate Area (km^2)	Reservoir Temperature °C #	Inferred Available Energy (PJ)
Kawerau	19 - 35	250 - 315	600 - 2200
Rotorua	10 -15	220 - 250	1000 -1500
Taheke	**5 - 9	200 - 230	100
Tikitere	12	230	300 - 600
Rotoma/Tikorangi	12	200	500 - 2200
Rotoma/Puhipuhi	38	170	1300
Waimungu/Rotomahana	20 - 30	*265	2500 - 3400

Temperature: Inferred average temperature over 2 km depth range
* Keewood (1991)
** Bromley (1996)

10.3 Kawerau Geothermal Field

The Kawerau geothermal field is the most heavily utilised field in the region. The field is located on the banks of the Tarawera River, 4 km north of Kawerau township (Figure 19). Natural thermal activity once consisted of hot springs, altered or steaming ground, steam and gas discharges from fumaroles, sinter, and hydrothermal eruption vents and deposits. Geothermal seepages occur along the Tarawera River but most of the thermal activity is concentrated in a 2km^2 area (Figure 19). Most of these thermal features are in a state of decline including the natural spring outflows (Healy 1974). The field was developed in the 1950s to supply energy to the Tasman Pulp & Paper Mill, which was constructed to be at a close proximity to the geothermal field. Most of the geothermal surface features have further declined as a consequence of the intense use of the field, or were damaged or destroyed during construction of effluent ponds.

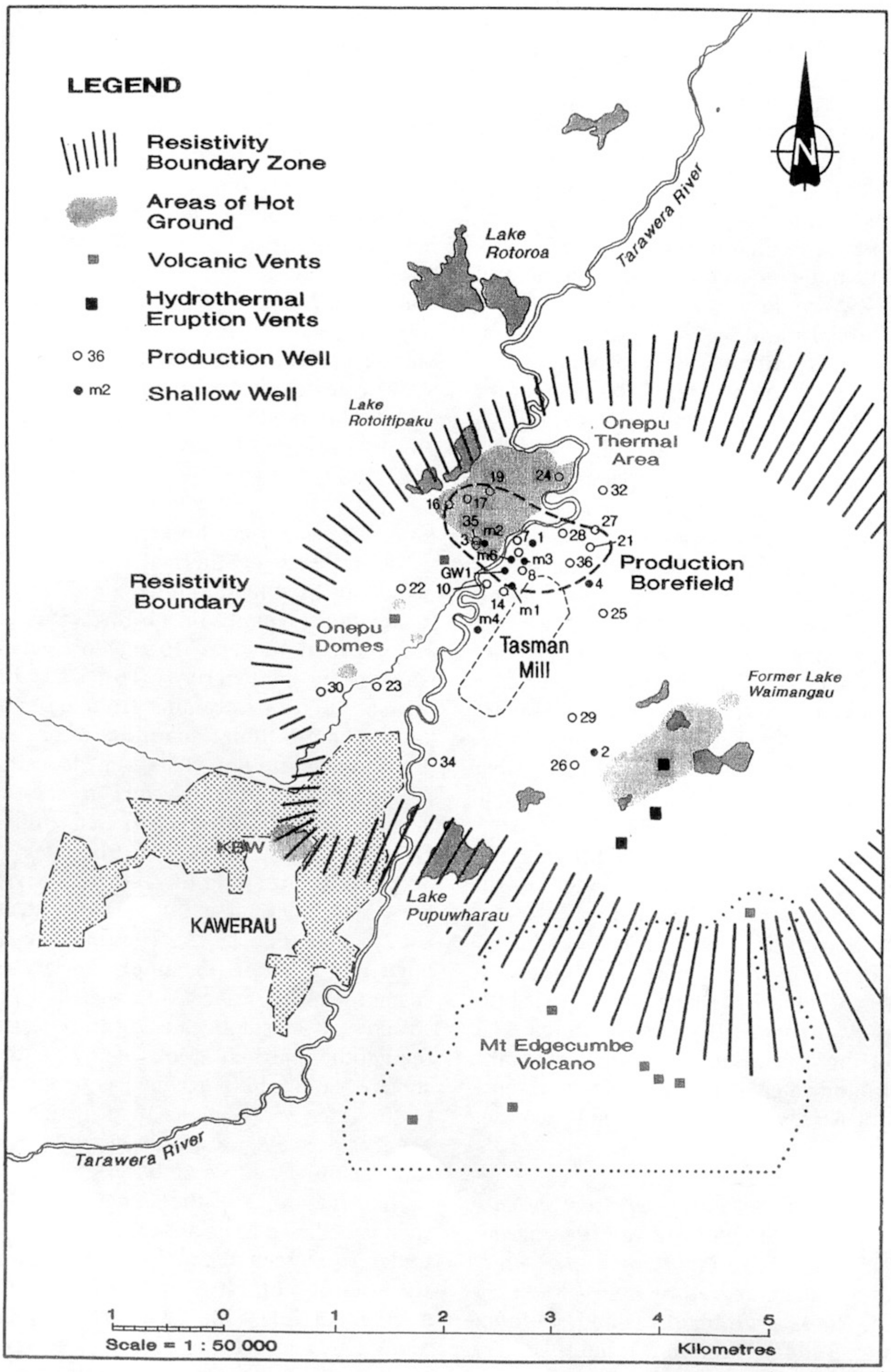


Figure 19 *Location and boundary of the Kawerau geothermal field and thermal areas, based on resistivity contours at 500m depth (from Wigley 1993)*

The heat source of the Kawerau geothermal field is considered to be a local magmatic source under Mt Edgecumbe and the deep outflow in the vicinity of Mt Tarawera. The main deep geothermal aquifer is found at depths of 900 - 1,500m, which has a transmissivity of 400 to 1,600 m^2/day. The deep aquifer is confined by overlaid volcanic ashes, tuff, breccias with ignimbrite sediment. A shallower geothermal aquifer up to 400 m in depth is found within volcanic rhyolite, ignimbrite, ashes, breccias and tuff formations.

The primary geothermal fluids (300 - 325°C) rises into the field along fissures in the basement greywacke. The geothermal fluids then spread laterally, where mixing occurs with cool groundwater recharge entering the field through shallow volcanic sediments (Nairn 1981). The mass recharge into the geothermal reservoir is estimated to be 6,000 to 7,200 m^2/day (Bixley 1991).

Over 32 wells have been drilled at Kawerau, with seven now operating as production bores. The depth range of the wells is 433 m to 1617 m, with a temperature range of 120°C to 310°C. Bores in the Kawerau field tend to decline in output because of mineral scaling and cold water inflow. These problems have been overcome by regular cleaning of the bores and deepening bores to enable a more reliable permeability (Cave et al. 1993). From 1997 over 33% of the separated geothermal fluid is re-injected. The remainder was discharged into the Tarawera River (O'Shaughnessey 1997), resulting in heat, and a small amount of contaminant (arsenic, ammonium nitrogen, boron, hydrogen sulphide lithium, silica), pollution. The discharge fluid to the river has been reduced because more geothermal fluid is re-injected back into the field and the construction of cooling ponds has reduced the heat load to the river.

10.4 Rotorua Geothermal Field

The Rotorua geothermal field is located at Rotorua City and underlies much of the city and the southern margin of Lake Rotorua. The Rotorua field is unique in that it contains New Zealand's last remaining area of major geyser activity, at Whakarewarewa (Allis and Lumb 1992).

Whakarewarewa and the heat from the Rotorua geothermal field are inextricably linked to the history, existence and identity of Rotorua City. Thermal activity has a special place in Maori culture, being used by the local Arawa people as a source of heat for cooking, bathing, food drying, processing flax fibres and medicinal purposes (Ministry of Energy 1985). Since European settlement in the early 1800s, the geysers and thermal features have gained world renown and attracts visitors to the Rotorua area. Rotorua is also know for its spas, and shallow geothermal bores have been drilled into the field to provide hot water for private homes, motels and other commercial and industrial uses.

Electrical resistivity and heat flow surveys suggest that the geothermal field extends northwards into Lake Rotorua and south of Whakarewarewa (Allis and Lumb 1992; Whitford 1992) (Figure 20).

The field is geologically located in the southern part of the Rotorua caldera, which collapsed after the eruption of the Mamaku Ignimbrite some 220,000 years BC (Houghton et al. 1995). This ignimbrite forms the base of the shallow geothermal aquifer system. The flow of geothermal fluids in the Rotorua field is largely controlled by the geological and geomorphic structure of the area. Hot alkali-chloride fluids appear to ascend from depth in the south part of the field via the Ngapuna and Roto-a-Tamaheke faults. Hot alkali-chloride fluids also enter the rhyolite domes from the ignimbrite in the east and in the north near Kuirau Park (Wood 1992). Isotopic geothermometry indicates that the deep up flow has temperatures of the order of 350°C at depths of 3-5 km beneath the field (Allis and Lumb 1992) before mixing with cold ground water at shallower depths of 200-500m. The mixing of the deep geothermal fluids with cool groundwater results in a fluid temperature of 120-220°C in the upper geothermal aquifers of the field (Wood 1992).

Natural surface feature activity is generally confined to three areas of the geothermal field; Whakarewarewa – Arikikapakapa to the south, Kuirau Park – Ohinemutu (on the shore of Lake Rotorua) to the north and Government Gardens – Ngapuna – Sulphur Bay and also on the shore of Lake Rotorua to the north east (Figure 20). Natural features across the field are generally alkali-chloride but areas of acid sulphate features occur as a result of steam heating of local groundwater.

Whakarewarewa thermal area has the most active and attractive thermal features and geyser activity and over 800 thermal features have been identified (Cody 2000). There are numerous alkali-chloride hot springs, hot and boiling pools, hot acid sulphate springs, mud cones and pools, lakelets, hydrothermal eruption craters, steaming and altered ground and extensive deposits of silica sinter, sinter aprons and terraces. Geyser activity is concentrated at Geyser Flat, which is a 6,000 m^2 tract of sinter-encrusted hot ground. Some of the named geysers are Pohutu, Te Horu, Prince of Wales Feathers, Mahanga, Waikorihihi, Kereru, and Wairoa. The largest and most spectacular, Pohutu Geyser, can erupt to an average height of 18 m (Cody and Lumb 1992).

The largest single physical feature at Whakarewarewa is Lake Roto-a-Tamaheke, which is hot lakelet supplied by hot chloride springs emerging through the bed of the lake and around its western and northern lake margins. The lake has a pH 3 - 4 as a result of the oxidation of dissolved H_2S in the geothermal fluid. There are also extensive areas of silica sinter and hydrothermal alteration around the lake. To the west of Whakarewarewa is Arikikapakapa thermal area which is underlain by a boiling zone and therefore most of the features in this area are steam heated (Cody and Scott, 1994). Features at Arikikapakapa include; extensive areas of steaming ground, numerous cool turbid acidic lakelets, boiling mud pools and barren solfatra.

In the north west of the field is the Kuirau park thermal area which contains a mix of weakly alkaline and acid features indicative of the mixing effect of steam heated and alkali-chloride waters (Cody, Scott 1994). The largest feature is Kuirau Lake that has an area of $5000m^2$. The lake is essentially a large alkali spring with a temperature range of 70-80°C. Outflow from the lake fluctuates but generally ranges from 25-50 L/s(Cody, Scott 1994). Other named features at the Kuirau thermal area include; Tarewa Springs, Soda Springs and Waiparuparu (Lobster pool). To the north of Kuirau thermal area is the Ohinemutu thermal area, where most thermal features are clear, alkaline springs and seepages around the lake edge.

On the north eastern end of the field is the Ngapuna – Sulphur Flats, Government Gardens thermal area. Features within this area tend to be acid-sulphate type but there are also alkaline-chloride springs at Government Gardens and the Ngapuna areas. The most significant feature is Rachael spring which, is a boiling and flowing(7-12 L/s) alkaline-chloride spring.

During the 1950s and 1960s geothermal energy was considered a cheap and convenient energy source. This resulted in an increase in bore drilling into the Rotorua field to abstract hot geothermal fluid. Most bores were drilled up to 200 m in depth into the shallow geothermal aquifer. Population growth and an energy crisis in the 1970s contributed to a significant increase in the bore drilling and at the peak there were 406 bores in use. Much of the geothermal energy use was inefficient, resulting in wastage of the geothermal heat (Ministry of Energy 1985). By the late 1970s there was a significant decline in activity at Whakarewarewa and other surface features across the field. For instance, in 1979 two major springs, Papakura and Korotiotio, failed (Grant-Taylor and O'Shaughnessy 1992). This decline was considered to be the result of the high withdrawal of geothermal fluid from the field from the large number of bores.

Public concern was expressed about the possible damaging effects on the activity of geothermal features at Whakarewarewa. The Minister of Energy and Rotorua District Council then announced, in 1980, guidelines for dealing with drilling and use of geothermal energy in Rotorua. This included a ban on drilling anything other than replacement wells within a 1.5 km radius of Pohutu Geyser (Figure 20). A monitoring programme was initiated by the Government in 1982 and the initial results of the monitoring indicated that a large fraction of geothermal energy abstracted from the field was wasted through inefficient use. As a result, the Rotorua Geothermal Taskforce was formed in 1983 to establish the extent of draw-off of geothermal fluid from the field and to investigate methods of reducing it (Ministry of Energy 1985).

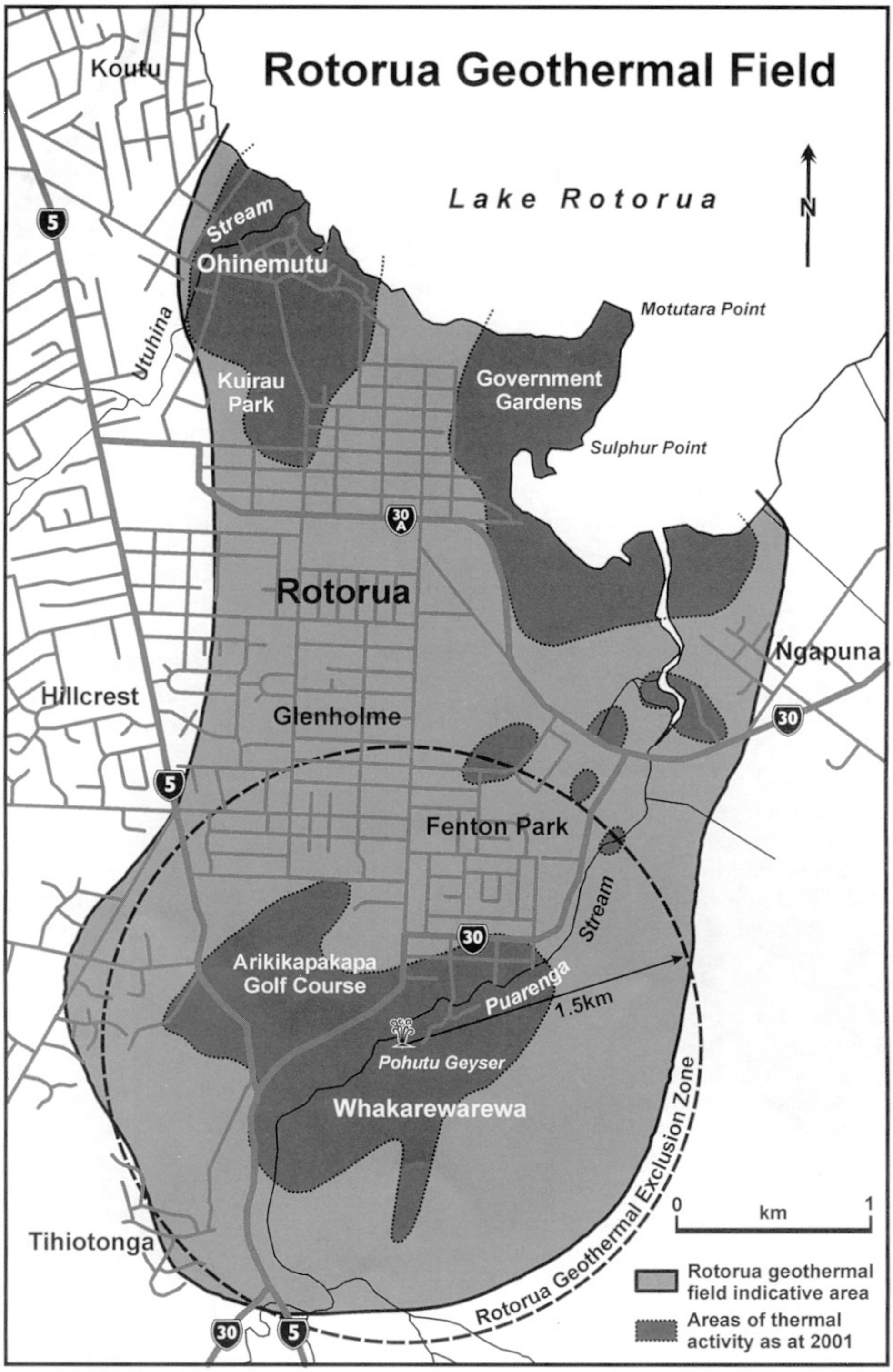


Figure 20 Location and boundary of the Rotorua geothermal field and main geothermal areas, based up on resistivity contours at 500m in depth (from Environment Bay of Plenty 1999)

Increasing concern over the effect of geothermal fluid withdrawal on the geysers at Whakarewarewa, and the apparent lack of action by local authorities, led the government to take emergency measures in 1986 by invoking its statutory authority. The government ordered the closure of all bores within a radius of 1.5 km of Pohutu Geyser and closure of all government department bores in Rotorua. The government also introduced a royalty regime for extracting fluid, which brought about a reduction in bore numbers from 406 to 141 by 1992 (Grant-Taylor and O'Shaughnessy 1992).

The total withdrawal from the field in 1985 was 31,000 tonnes/day, representing 40% of the natural up-flow; this was reduced to less than 9,500 tonnes/day by 1992 (O'Shaughnessy 1997). Following bore closure there was a marked increase in water level, or pressure head, across the field occurred (Figure 21). On average the water level, or pressure, in monitoring bores across the field increased by 1 to 2 metres for the period from 1986 to 1988. Water levels then remained relatively stable until 1993. From 1993 there has been a gradual increase in water level in monitoring bores of approximately 0.5 m. This increase is considered to be due to increases in the quantity being re-injected (O'Shaughnessy 2000) and the field continues to adjust to a new equilibrium.

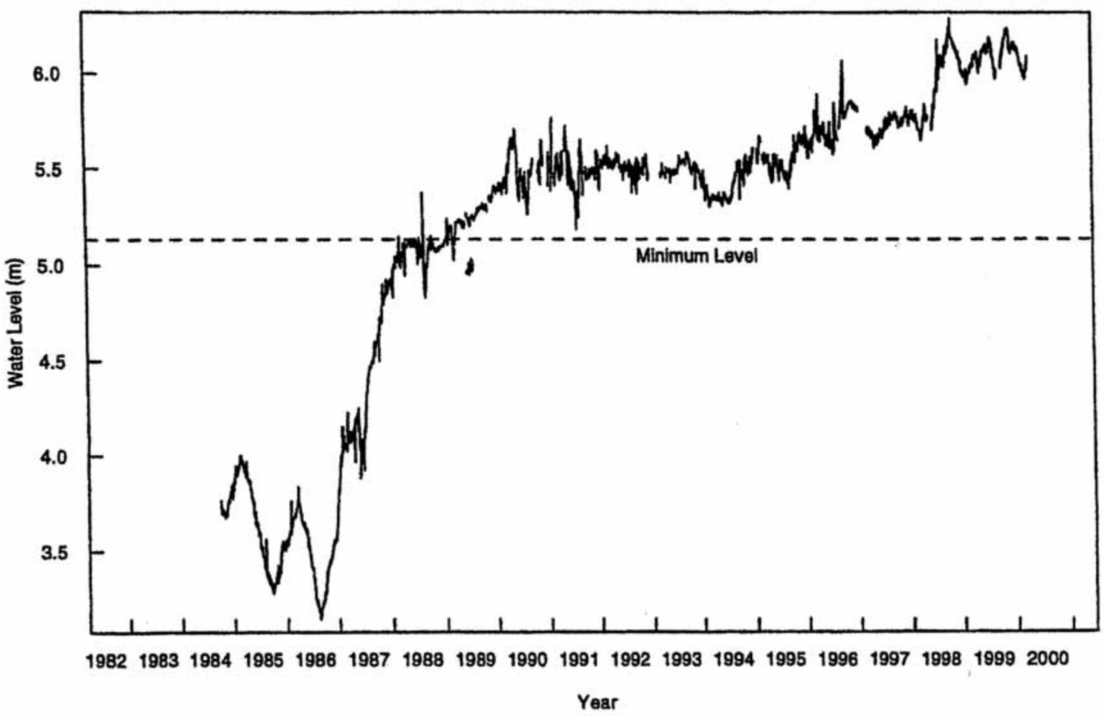


Figure 21 Changes in water level (pressure) in the Rotorua geothermal field as reflected in Environment Bay of Plenty monitoring bore M16 (from Kissling 2000)

Increased outflow at Whakarewarewa was observed following bore closures. This increased outflow was estimated to be between 950 and 2,750 tonnes/day (Grant Taylor et al. 1992). Many of the geothermal features at Whakarewarewa responded quickly to field pressure recovery, with increased activity from geysers and resumption of spring flows similar to historic levels (Cody and Lumb 1992). Similar recovery of surface features has also been observed across the other thermal areas of the field.

The recovery of surface features has demonstrated that the preservation of aquifer pressure is important in maintaining surface features. Increases in thermal activity across the field have continued, with unprecedented eruption activity from Pohutu geyser and the resumption of spring flow. In 1998, Tarewa springs in Kuirau Park thermal area reactivated, resulting in damage to property. A hot spring began flowing under the garage floor of home units at Tarewa Road. This together with associated geyser activity from adjacent springs, resulted in the need for demolition and removal of the dwelling concerned. Investigations showed that the dwelling had knowingly been built on a geothermal feature (Cody 1998). This highlighted the risk of property damage as the field recovered.

10.5 Other High Temperature Geothermal Fields

10.5.1 Rotoma-Tikorangi

The Tikorangi field has been identified by resistivity surveys and is located between Lakes Rotoehu and Rotoma in the north and in an elonged shape to the Tarawera River to the south (Bromley et al, 1988). The major thermal features of the Rotoma-Tikorangi field are warm springs (22-50°C). The most notable activity is the Waitangi Springs and warm seepages along the southeastern shore of Lake Rotoehu, and Otei Springs on the southern shore of Lake Rotoma. Most of the springs discharge large flows (up to 53 L/s) of warm dilute sodium bicarbonate chloride waters (Nairn 1981). The main Waitangi hot spring discharges weakly acid chloride-bicarbonate water at 50°C, with a heat flow of 8 MW (Nairn 1999). Solfataric activity (sulphur pans), hydrothermally altered ground, fumaroles (>90°C) and patches of steaming ground occur in a small confined area known as the Tokorangi thermal area (Nairn 1981, 1999).

The thermal area to the south is known as Te Haehaenga basin, contains weakly mineralised warm springs (Nairn 1981), and areas of warm swampy ground occurs along the Tarawera River (Bromley et al. 1988). The springs have a deep chloride signature but this is highly diluted because of mixing with large quantities of shallow groundwater (Nairn 1981, 1999).

10.5.2 Rotoma-Puhipuhi

Puhipuhi geothermal field is located 8 km east of Lake Tarawera and the Haroharo Caldera. The field was identified from geophysical surveys during investigations for prospective geothermal resources by Fletcher Challenge in the late 1980s. Few present-day natural features can be found, but there is some hydrothermal alteration on the Puhipuhi hills and warm springs at Waiaute west of the Puhipuhi hills. These springs range in temperature from 16°C to 23°C and have a chloride content of 20 to 81 mg/L. The springs are associated with very large discharges of cold shallow groundwater and the chemistry of the warm springs indicates large dilution of the geothermal waters. The lack of thermal features suggests that the field is a declining geothermal system. However, geothermometry on samples from the Waiaute springs indicates higher subsurface temperatures (Nairn, 1981).

10.5.3 Taheke

The Taheke geothermal field, located 20 km north of Rotorua City, is a relatively small field and available data suggests that the field has a limited heat output. Taheke may be connected to the Tikitere geothermal field to the north (Espanola 1974). The main reservoir for the field lies between about 400 m and 2 km depth and is inferred to be a two-phase (steam and water) system (Bromley 1994). The natural features consist of hydro-thermally altered ground fumaroles, small springs and hot pools with temperatures ranging between 57-97ºC.

Flowing springs (6-8 L/s) and pools of the field are a mixture of bicarbonate and acid sulphate condensate water (Espanola, 1974), (Glover, R.B, 1974).

10.5.4 **Tikitere**

The Tikitere geothermal field, located about 16 km northeast of Rotorua City, includes the well-known "Hells Gate" tourist thermal area and the Ruahine Springs 2.5 km to the northeast (MacDonald 1974; Cave et al. 1993). The natural features of the field are boiling springs and hot pools, seepages, steaming and hydrothermally altered ground, fumaroles, sulphur deposits and gas discharges. Natural hot pools are commonly turbid and usually boiling, with temperatures between 38°C to 100°C. Several shallow bores (70 m to 120 m) near Hells Gate discharge steam and hot chloride water, for space heating, pools and private baths.

10.5.5 **Waimangu/Rotomahana**

The Waimangu/Rotomahana geothermal field is located 22 km southeast of Rotorua and has the most prominent geothermal features in the Okataina Volcanic Centre (Simmons et al. 1994). Surface activity at the Waimangu geothermal field occurs near the intersection of the caldera structure and within the 17km-long line of volcanic craters across Mt Tarawera and through Lake Rotomahana. The field and the present Lake Rotomahana were formed during the Tarawera basaltic rift eruption on 10 June 1886 (Wood 1994). The Waimangu Valley is a well known tourist spot for viewing thermal activity and is renowned for its diversity of thermal features.

Thermal activity in the Waimangu Valley consists of numerous alkali-chloride hot springs, hot and boiling pools, hot acid-sulphate lakes, hydrothermal eruption craters, steaming and altered ground and minor silica deposits and sinter terraces. Some of the named features in the Waimangu thermal area include; “Black Crater” – steaming ground; “Echo Crater” containing a small (38,000m^2) shallow (10-20cm deep) alkali-chloride Lake (“Frying Pan Lake”) 45-55°C; “Fairy Crater” – explosion crater; “Inferno Crater” containing a small (7,500m^2) shallow (29m deep) acid chloride-sulphate lake (Inferno Crater Lake”) 37-84°C; “Raupo Pond Crater” – explosion crater (hydrothermal eruption May 1981); “Southern Crater” warm ground; “Warbrick Terrance” – siliceous sinter apron with hot springs. Hot steaming and altered ground, hot and boiling springs and seeps, also occur along the western shore of Lake Rotomahana known as the “Steaming Cliffs” thermal area; hot springs also occur on the bottom of “Lake Rotomahana” (Scott B.J, 1994), (Hunt et. al, 1994).

Waimangu is also known for hydrothermal eruptions and large short-lived geyser activity. The Waimangu Geyser played between 1,900 and 1904 in the eastern part of Echo Crater, with eruptions up to 400m high. Large hydrothermal eruptions occurred in 1917 that lasted 3 days and erupted a depression now occupied by the present Frying Pan Lake. The Lake fills a depression in the western part of Echo Crater and is one of the largest natural thermal features in the Taupo Volcanic Zone discharging 100-120 L/s of chloride sulphate water at or about 50°C. However, most of the springs and pools in the Waimangu thermal area discharge less than 1.0 L/s (Simmons et al, 1994).

The Waimangu field is now protected from development and the thermal activity in the Valley is managed as scenic reserve. The thermal features in the Valley have been catalogued and in recent years the field and thermal features have been closely monitored and studied.

10.5.6 **Rotokawa**

Rotokawa geothermal field is located 8 km northeast of Rotorua City and lies within the Rotorua caldera. Hot springs discharge into the nearby Lake Rotokawa and warm springs discharge into Lake Rotorua near the present airport. The hot springs that discharge into Lake Rotokawa are slightly acidic (pH 5.5) with moderate chloride and have temperature ranging between 45-52°C (Glover 1974). A number of bores from 45 m to 99 m in depth have been drilled and the water is used for spa pools, space heating, greenhouses and hotel developments. Discharge temperatures from the bores range from 29°C to 99°C, with the majority of the deeper bores are flowing artesian. Geochemical evidence suggests that the deep reservoir is 160°C chloride water (Glover 1974).

10.5.7 Lake Rotoiti

The Lake Rotoiti geothermal area is located 19 km northeast of Rotorua City and is thought to be structurally related to the Tikitere graben and Haroharo caldera (Nairn 1974, 1999). The geothermal area underlies much of the lakebed of Lake Rotoiti. The highest heat flow occurs in the floor of the centre lake basin, which occupies about 2 km^2 and coincides with the deepest part of the lake (70 to 120 m in depth). Temperatures of up to 130°C have been measured in the lake sediments by Calhaem (1973), and a thermal gradient of 63°C/m was calculated.

10.5.8 Matata

No natural thermal features have been identified at Matata, but a low-resistivity anomaly has been identified. A bore drilled on behalf of the Ministry of Energy in 1986 failed to find high temperatures (Cave et al.1993).

10.5.9 Motuhora Island (Whale Island)

Motuhora Island (Whale Island) is located 8 km offshore from the Bay of Plenty coast and is an eroded Quaternary andesite-dacite strato consisting of a central cone and an intruded lava dome. A range of thermal features occur on the island; hydrothermally altered ground, steaming ground, fumaroles, sulphur deposits, silica sinter, and hot water springs. Temperatures of 98.5°C have been recorded in hot water flows and temperatures above 100°C have been recorded in fumaroles (Lloyd 1974).

The most significant activity is limited to the southwest flank of the central cone known as Sulphur Valley where there are fumaroles, sulphur deposits and in the lower valley hot springs and associated sinters deposits (Lloyd, 1974). Sulphur was mined in early 1900’s but the island is now protected and managed as a reserve (Department of Conservation, 1999).The extent of the geothermal activity is not known and therefore the Island is defined as a hot water occurrence.

10.5.10 Whakaari (White Island)

Whakaari (White Island) is an active composite andesitic volcano located about 50 km offshore from Whakatane. It consists of two overlapping cones, cut by a large breached crater on the eastern side of the island (Clarke and Cole 1986). Thermal activity is found within the crater complex and consists of numerous high-temperature fumaroles depositing sulphur, ephemeral mud pools and springs, and thermally altered ground (Mongillo and Clelland 1984). Springs and pools on the crater floors contain high quantities of free acids and sometimes boil vigorously. In the past the Island was mined for sulphur but it is now managed as a private scenic reserve. The temperature of fumarole activity ranges from 100°C to 350°C, with gas discharges of mostly carbon dioxide and sulphur dioxide, and associated sulphur deposition.

11 Management of Geothermal Resources

Environment Bay of Plenty is responsible for the sustainable management of all geothermal resources of the region, so that their potential, quality and attributes are retained and protected. Some of the geothermal resources in the region are protected from extractive use, while others are available for use and development, within the constraints of providing for the protection of significant features and avoiding any adverse effects. To guide resource users and to assist with the development of regional plans and the assessment of resource consent applications, all known geothermal resources in the region have been classified (table 1.2), according to their values and uses, resulting in four different Geothermal Protection Levels (Environment Bay of Plenty 1999b, 2000):

- GPL 1 - Complete preservation of the natural, intrinsic, scenic, cultural, heritage and ecological values;
- GPL 2 - Preservation and restoration of the natural, intrinsic, scenic, cultural, and heritage values by increasing the geothermal field pressures and the appropriate conservation and management of surface features;
- GPL 3 - The use (including abstraction) of geothermal water and heat energy where the adverse effects can be avoided, remedied or mitigated;
- GPL 4 - The use (including abstraction) of geothermal resources where the adverse effects of taking and discharging geothermal resources on the environment are avoided, remedied or mitigated.

Table 1.2 Protection status of geothermal resources in the Bay of Plenty Region

Geothermal System	Type	Protection Level (GPL)
Awakeri	Hot water occurrence	4
Kawerau	Geothermal field	3
Lake Rotoiti	Geothermal area	3
Manaohau	Hot water occurrence	4
Matata	Geothermal prospect	4
Mayor/Tuhua Island	Hot water occurrence	4
Moutohora Island (Whale Island)	Hot water occurrence	1
Papamoa/Maketu	Geothermal field	4
Pukehinau	Hot water occurrence	4
Rotokawa	Geothermal field	3
Rotoma/Puhi Puhi	Geothermal field	3
Rotoma/Tikorangi	Geothermal field	3
Rotorua	Geothermal field	2
Taheke	Geothermal field	3
Tauranga	Geothermal field	4
Tikitere	Geothermal field	3
Waimungu/Rotomahana	Geothermal field	1
Whakaari (White Island)	Geothermal area	1

Environment Bay of Plenty is developing a regional plan that will include policy, method, and rules for managing the geothermal resources of the region. The Rotorua geothermal field, however, is managed under a separate specific regional plan.

11.1 Rotorua Geothermal Plan

The former Bay of Plenty Catchment Commission developed the Rotorua Geothermal Field Management Plan in late 1988, but it could not be implemented effectively because as it was a non-statutory plan. Environment Bay of Plenty (Bay of Plenty Regional Council) was formed in 1989 and inherited management responsibility for the field. With the imminent introduction of the Resource Management Act in October 1991, research was initiated and Environment Bay of Plenty began developing the Rotorua Geothermal Regional Plan. Unlike the preceding plan, this regional plan was a statutory document that would allow Environment Bay of Plenty to develop aims, objectives, policies and methods for managing the field, in consultation with the community. Due to the past history of bore closure, there was still much scepticism surrounding regulatory controls on the field. Section 32 of the Resource Management Act 1991 required Environment Bay of Plenty to have robust scientific information to support policy initiatives for a resource management plan for the geothermal field. It has been conservatively estimated that, between 1982 and 1999, $3.75 million has been spent on research and management of the field (Environment Bay of Plenty 1999b).

The Rotorua Geothermal Plan was proposed in December 1993, but the plan was appealed to the Environment Court in 1998. After the settling of appeals by the Environment Court, the plan became operative in July 1999. The aims of the Operative Rotorua Geothermal Regional Plan are to ensure that the Rotorua geothermal resource retains its value and potentials while protecting geothermal surface features; protecting tikanga Maori; identifying and, as practical, enhancing available geothermal resources; providing for the allocation of that resource for present and future efficient use; and managing and controlling all adverse effects on the field (Environment Bay of Plenty 1999b). Some of the key polices of the plan are:

- retention of the 1.5-km radius zone around Pohutu Geyser prohibiting mass abstraction, to protect the outstanding geothermal features at Whakarewarewa;
- no net increase in abstraction from the field;
- reinjection of all fluid where practicable;
- setting of a strategic level in the geothermal aquifer to sustain geothermal surface features and protect the resources into the future;
- protection of surface features from physical destruction and restoration of outflows and avoidance of mitigation of natural geothermal hazards.

The plan is due for a full review commencing July 2004 (Environment Bay of Plenty 1999b).

References

ALLIS, R.G.; LUMB J.T. 1992: The Rotorua Geothermal Field, New Zealand: Its physical setting, hydrology and response to exploitation. Geothermics Special Issue 21 No. 1/2: 7-24.

ALLIS, R.G.; CHRISTENSON, B.W.; NAIRN, I.A.; RISK, G.F.; WHITE, S.P. 1993: Proceedings of the 15th New Zealand Geothermal Workshop.

BIXLEY, P.F. 1991: Hearing evidence to Environment Bay of Plenty's Regulation and Monitoring Committee, August 1991. Environment Bay of Plenty, File Reference 1370 02 2443.

BRIGGS, R.M.; HALL, J.G.; HARMSWORTH, G.R.; HOLLIS, A.G.; HOUGHTON, B.F.; HUGHES, G.R.; MORGAN, M.D.; WHITEBREAD-EDWARDS, A.R. 1996: Geology of the Tauranga Area, Sheet U14 1:50 000, Occasional Report No. 22 Department of Earth Sciences, University of Waikato Hamilton. New Zealand. 56 p

BROMLEY, C.A.; BOTTOMLEY, J.J.; PEARSON C.F. 1988: Geophysical exploration for prospective geothermal resources in the Tarawera Forest. Proceedings of the 10`" New Zealand Geothermal Workshop. 123-128.

BROMLEY, C. 1994: Taheke geothermal field scientific resource assessment. Unpublished report for consent application hearing. Environment Bay of Plenty File No. 1370 4142. 14p.

CALHAEM, I.A. 1973: Heat flow measurements under some lakes in the North Island, New Zealand. PhD thesis, Victoria University Library, Wellington. 191 p.

CARRYER and ASSOCIATES LTD 1997: Report on a pumping test carried out at Troutbeck Road, Galatea. Unpublished report prepared for Winstone Aggregates Ltd. 8 p.

CAVE, M.P.; LUMB J.T.; CLELLAND L. 1993: Geothermal Resources of New Zealand. Resource Information Report 8, Energy and Resources Division, Ministry of Commerce, New Zealand. 39 p.

CLARKE, R.H.; COLE J.W. 1986: White Island. In: Smith, I.E.M. (ed.) Late Cenozoic Volcanism in New Zealand. Royal Society of New Zealand Bulletin 23: 169178.

CODY, A.D. 1998: No. 20 Tarewa Road conditions report. Unpublished report to GAB Robins NZ Ltd. 13 p.

CODY, A.D.; LUMB, J.T. 1992: Changes in thermal activity in Rotorua geothermal field. Geothermics 21 No. 1/2: 215-230.

DAVIES, J.E.; AHLERS, W.W.; DEELY, J. 1994: Arsenic in drinking water: investigation of at risk supplies. Report prepared for the Ministry of Health, Institute of Environmental Science and Research Report CSC 96/1. 62 p.

DEPARTMENT OF CONSERVATION 1999: Moutohora (Whale) Island Conservation Management Plan 1999-2009. Department of Conservation, Rotorua. 64 p.

ENVIRONMENT BAY of PLENTY 1990: Te Puke-Maketu groundwater resource evaluation. Unpublished Technical Publication No. 1, prepared by W. Russell and C. O'Brian. 60 p.

ENVIRONMENT BAY OF PLENTY 1991: Rangitaiki Plains groundwater resource evaluation. Unpublished Technical Publication No. 2 prepared by S. Hodges, C. O'Brian, B. O'Shaughnessy, and A. Wilson. 140 p.

ENVIRONMENT BAY of PLENTY 1994a: Geothermal groundwater resource of the Western Bay of Plenty. Unpublished Environmental Report No. 94/22, prepared by Sean Hodges. 37p.

ENVIRONMENT BAY of Plenty 1994b: Groundwater resources of the Lower Tarawera Catchment, Environment Bay of Plenty, Environmental Report 94/3, prepared by L. Pang. 149 p.

ENVIRONMENT BAY of PLENTY 1999a: Operative Bay of Plenty Regional Policy Statement. Environment Bay of Plenty. Whakatane. 220 p.

ENVIRONMENT BAY of PLENTY 1999b: Operative Rotorua Geothermal Plan: Environment Bay of Plenty, Whakatane.142 p.

ENVIRONMENT BAY of PLENTY 2000: Draft Water and Land Plan, Environment Bay of Plenty, Whakatane. 334 p.

ENVIRONMENT BAY of PLENTY 2002: Land Application of Dairy Shed Effluent and Effects on Groundwater Quality, Environmental Report 2002/09, prepared by John McIntosh and Dougall Gordon, Whakatane.74 p.

ESPANOLA, O.S. 1974: Geology and hot springs of Tikitere and Taheke hydrothermal fields, Rotorua, New Zealand. New Zealand Geological Survey Report No. 68, Department of Scientific and Industrial Research, New Zealand. 76 p.

GLOVER, R.B. 1974: Geochemistry of the Rotorua geothermal district. In: Geothermal Resources Survey - Rotorua Geothermal District, Department of Scientific and Industrial Research Geothermal Report No. 6, Department of Scientific and industrial Research Wellington. 108-110.

GRANT-TAYLOR, D.F.; O'SHAUGHNESSY, B.W. 1992: Rotorua geothermal field: response of field since closure (1987 1992). Technical Publication No. 7 Environment Bay of Plenty, Whakatane. 57 p.

GROUNDWATER CONSULTANTS (NZ) LTD 1985a: Western Bay of Plenty groundwater resource evaluation: Stage 2 exploratory drilling programme Katikati-Kauri Point region final report. 28 p.

GROUNDWATER CONSULTANTS (NZ) LTD 1985b: Investigation towards improvement of the town water supply at Athenree Bay of Plenty. Unpublished report to Tauranga County Council. 15 p.

GROUNDWATER CONSULTANTS (NZ) LTD 1989: Construction and evaluation of test production well for a community water supply - Waihi Beach. Unpublished Report for the Ohinemuri County Council. 21 p.

HEALY, J. 1974: Kawerau geothermal field. *In*: Staff of New Zealand Geological Survey. Minerals of New Zealand (Part D: geothermal). New Zealand Geological Survey report 38D.

HOUGHTON, B.F.; CUTHBERTSON, A.S. 1989: Sheet T14 BD Kaimai. Geological Map of New Zealand, I: 50 000. Map (*I* Sheet) and notes. Department of Scientific and Industrial Research, Wellington, New Zealand. 35 p.

HOUGHTON, B.F.; WILSON, C. J.N.; MC WILLIAMS, M.O.; LAMPHERE, M.A.; WEAVER, S.D; BRIGGS, R.M.; PRINGLE, M.S. 1995: Chronology and dynamics of a large silicic magmatic system: central Taupo Volcanic Zone, New Zealand. Geology 23:13-16.

HUNT, T.M.; TOSHA, T. 1994: Precise gravity measurements at Inferno Crater Waimungu, New Zealand. Geothermics Special Issue 23 No. 5/6: 573-582.

KEAR D.; ROSS, J.B. 1961: Boron in New Zealand coal ashes. New Zealand Journal of Science 4: 360-380.

KEEWOOD, M. 1991: The geology of the Waimangu field. Unpublished MSc Thesis, University of Auckland. 148 p.

KISSLING, W.M. 2000: Rotorua geothermal monitoring programme -summary of data for the period January 1998 to April 2000. Unpublished Industrial Research Report No. 1994 to Environment Bay of Plenty. Applied Mathematics Group, Industrial Research Limited, Lower Hutt. 58 p.

HUNT, T.M.; BIBBY, H.M. 1992 : Geothermal Hydrology. In: Waters of New Zealand. New Hydrological Society, Wellington. 147-166.

LLOYD, E.F. 1974: Whale Island geothermal field. In Minerals of New Zealand, A summary of resources and prospects Part D, Geothermal Resources, by staff of the New Zealand Geological Survey, NZ Geological Survey Report 38D, Rotorua. 5 p.

MACDONALD, W.J.P. 1974: Geothermal Resources Survey Rotorua Geothermal District. Department of Scientific and Industrial Research Geothermal Report No. 6. Department of Scientific and Industrial Research, Wellington. 68 p.

MINISTRY OF ENERGY 1985: The Rotorua geothermal field. A report of the Geothermal Monitoring Programme and Task Force 1982-1985. Oil and Gas division, Ministry of Energy, Wellington. New Zealand. 493 p.

MINISTRY of HEALTH 1995: Drinking-Water Standards for New Zealand 1995. 87p.

MINISTRY of WORKS AND DEVELOPMENT 1985: Galatea pastoral irrigation scheme prefeasibility study report, prepared by R.A. Burnett and F.O. Campbell. 72 p.

MONGIOLLO, M.A.; CLELLAND, L. 1984: Concise listing of information on thermal areas and thermal springs of New Zealand. Department of Scientific and Industrial Research. Geothermal Report Number 9. 228 p.

NAIRN, I.A. 1974: 3.5 Lake Rotoiti Geothermal Field. In: Minerals of New Zealand. A summary of resources and prospects, Part D, Geothermal Resources, by staff of the Geological Survey, New Zealand Geological Survey Report 38D, Rotorua. 5 p.

NAIRN, I.A. 1981: Geothermal resources of the Okataina volcanic centre. New Zealand Geological Survey, Rotorua, New Zealand. 41 p.

NAIRN, I.A. 1999: Geology of the Okataina Volcanic Centre - An explanation to accompany the Environment Bay of Plenty GIS data set. Institute of Geological and Nuclear Sciences Limited, Lower Hutt. 148 p.

NAIRN, I.; BEANLAND, S. 1989: Geological setting of the 1987 Edgecumbe earthquake, New Zealand. New Zealand Journal of Geology and Geophysics 32: 1-13.

O'SHAUGHNESSY, B.W. 1997: Compliance report - Crown Geothermal Consents for the Kawerau Geothermal Field. Environment Bay of Plenty Report 97/14. 26 p.

O'SHAUGHNESSY, B.W. 2000: Use of economic instruments in management of Rotorua geothermal field, New Zealand. Geothermics 29 No. 4/5 529-555.

PANG, L.; CLOSE, M.; SINTO, L. 1996: Protection zones of the major water supply springs in the Rotorua District for the Rotorua District Council. Unpublished Institute of Environmental Science and Research Report CSC 96/1. 77 p.

PATTLE DELAMORE PARTNERS LTD 1996: Preliminary water allocation strategy for the Galatea Basin. Unpublished report prepared for Environment Bay of Plenty. 35 p.

ROSEN, M.R.; MILNER, D.; WOOD, C.P.; GRAHAM, D.; REEVES, R. 1998: Hydrogeological investigation of groundwater flow in the Taniwha Springs area. Unpublished Geological and Nuclear Sciences report prepared for the Rotorua District Council. 25 p.

ROTORUA DISTRICT COUNCIL 1993: Report on rural land use practices in the Rotorua District, prepared by Sigma Consultants. 200 p.

SIMMONS, S.F.; STEWART M.K.; ROBINSON, B.W.; GLOVER, R.B. 1994: The chemical and isopotic compositions of thermal waters at Waimangu, New Zealand. Geothermics Special Issue 23 No. 5/6: 539-554.

SIMPSON, M.P. 1987: Heat flow measurements on the Bay of Plenty coast, New Zealand. Journal of Volcanology and Geothermal Research 34: 25-33.

SIMPSON, B.; STEWART M.K., 1987: Geochemical and isotope identification of warm groundwaters in coastal basins near Tauranga, New Zealand. Chemical Geology 64: 67-77.

SKINNER, D.N.B. 1986: Neogene volcanism of the Hauraki Volcanic Region. *In* Smith I.E.M (ed.) Late Cenozoic volcanism in New Zealand. Royal Society of New Zealand Bulletin 23: 21-47.

WHITFORD, P.C. 1992: Heat flow in the sediments of Lake Rotorua. Geothermics 21 No. 1/2 75-88.

WIGLEY, D.M. 1993: Kawerau Geothermal Field Management Strategy - Draft May 1993, prepared for Bay of Plenty Regional Council. Works Geothermal, Wairakei, Taupo. 65 p.

WOOD, C.P. 1992: Geology of Rotorua geothermal system. Modelling mass, energy and chloride flows in the Rotorua geothermal system. Geothermics 21 No. 1/2 25-42.

WOOD, C.P. 1994: Aspects of the geology of Waimanagu, Waiotapu, Waikite and Reporoa geothermal systems, New Zealand: Background and History. Geothermics Special Issue 23 No. 5/6: 401-524.

WOODWARD, D. 1988: Seismic reflection survey on the Rangitaiki Plains, Eastern Bay of Plenty, New Zealand. Geophysics Division, Department of Scientific and Industrial Research Report 218. 12 p.

WOODWARD-CLYDE (NZ) LTD 1991: Assessment of yields Athenree Quarry wells. Unpublished report to the Western Bay of Plenty District Council. 16 p.