

Case History No. 9.9. The Wairakei Geothermal Field, New Zealand, by Paul F. Bixley, Ministry of Works and Development, Wairakei, New Zealand

9.9.1 INTRODUCTION

The Wairakei geothermal area is located 8 km north of Lake Taupo in the center of the North Island of New Zealand (Figure 9.9.1). Geothermal investigations at Wairakei began in 1950 and culminated with the commissioning of the first stage of the power station in 1958 and the second stage in 1964 bringing the installed capacity to 192 MWe. Steam is supplied to the power station by 64 wells, most of which produce a steam-water mixture at the wellhead. The mixture is separated, the steam piped to the power station and waste water dumped into the Waikato River. The 64 production wells cover an area of 2 km² referred to in this paper as the "production field."

The first indication of ground movement came in 1956 when discrepancies were found in the levels of several benchmarks since the previous survey in 1950 (Hatton, 1970). One benchmark had subsided 76 mm. A levelling network was established and gradually expanded until by 1971, the most recent comprehensive survey, the area of subsiding ground was found to exceed 30 km². Within this area were two zones of relatively rapid subsidence; one immediately north of the eastern production field and the other at Karapiti, a region of natural thermal activity about 3 km south of the production field. Economic interest has centered on the zone of rapid subsidence northeast of the production field, as steam mains to the power house, and channels carrying separated water pass across this zone. Benchmarks in this zone are levelled to third order standards annually (third order accuracy is within 12 mm/√km, where km is kilometres of line traversed).

9.9.2 GEOLOGY

The geology of the Wairakei geothermal field has been discussed in detail by Grindley (1965). The production field is underlain by a near flat sequence of acid volcanics, consisting of six basic units down to 1.2 km (most wells are drilled to 600-1200 m, one well is drilled to 2.5 km). These units are: Recent Pumice, Wairakei Breccia, Huka Falls Formation, Haparangi Rhyolite, Waiora Formation and Wairakei Ignimbrites. Almost all production comes from within the Waiora Formation where active faults have been intercepted by drillholes (Grindley, 1965). There is also evidence for a permeable zone in the Waiora Breccia just above the Wairakei Ignimbrite contact (Bolton, 1970).

WAIRAKEI IGNIMBRITES: Hard welded ash flow tuff, thickness 950 m in the single hole penetrating this formation.

WAIORA FORMATION: Pumice sandstone, pumice breccia and thin (up to 70 m) ignimbrite sheets. Total thickness 400 m in the western section of the production field, thickening rapidly to the east to greater than 750 m.

HAPARANGI RHYOLITE: An extensive rhyolite sill, intruded into the Waiora Formation to the west of the production area. Maximum thickness 450 m.

HUKA FALLS FORMATION: Bedded mudstone and tuffaceous sandstone; thickness 60-220 m.

WAIRAKEI BRECCIA: Chalazoidite and vitric tuff conformably overlying the Huka Falls Formation; differentiated from the Huka Falls Formation by the incoming of chalazoidites. Maximum thickness 170 m.

RECENT PUMICE: Superficial deposits up to 30 m thick, consisting of alluvium derived from the dissection of underlying formations together with ash and pumice/lapilli shower material.

The relationship between these units is shown on the cross section ABC (Figure 9.9.2).

The age of the above sequence ranges from lower-mid Pleistocene for the Wairakei Ignimbrites to possibly as young as 20,000 years BP for the Wairakei Breccia (Browne, 1973).

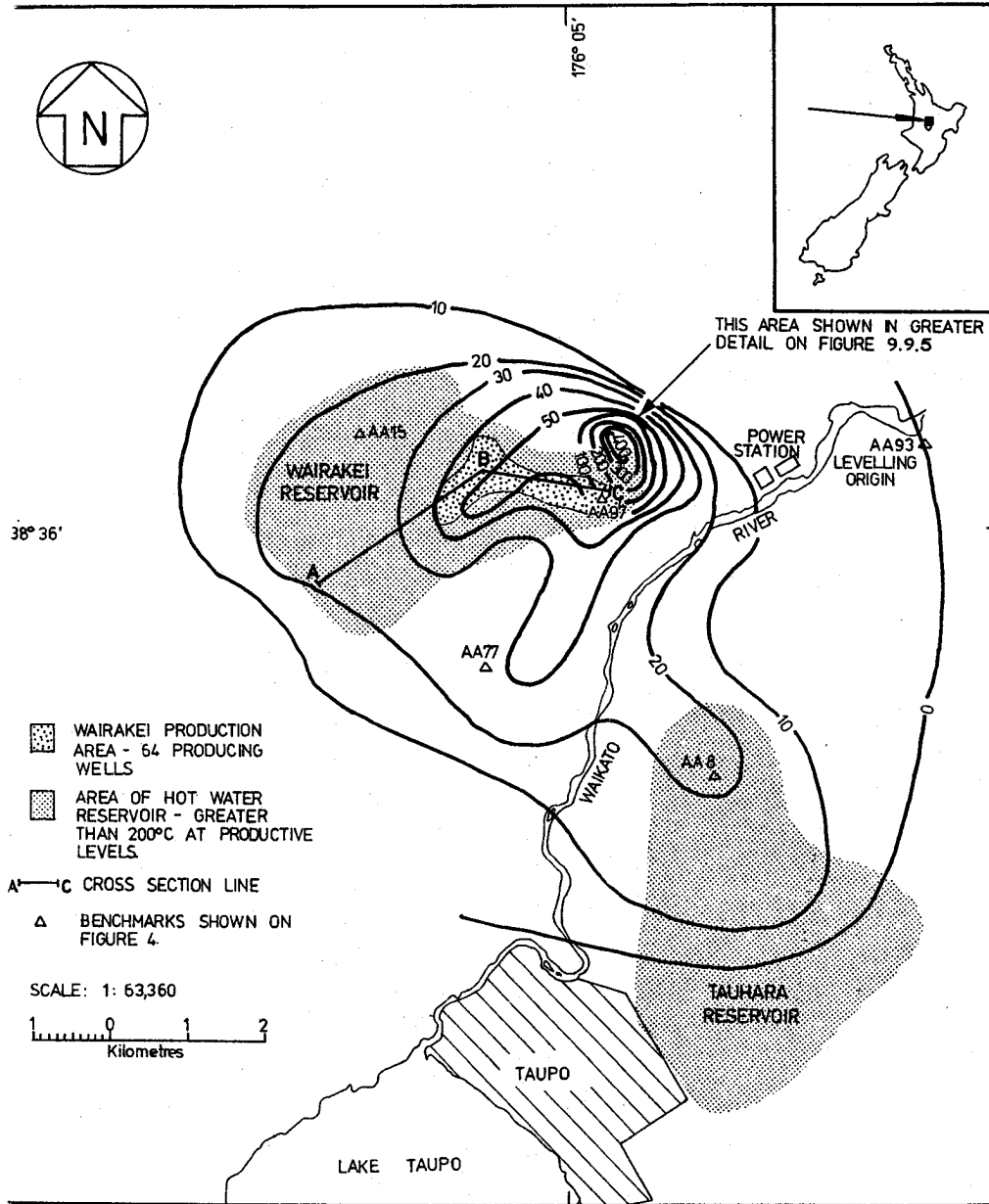


Figure 9.9.1 Land subsidence 1956 to 1971, of Wairakei-Tauhara geothermal areas, New Zealand. Lines of equal subsidence in millimetres per year. Reservoir boundaries are taken as the estimated 2000 temperature contour at the production level, based on surface resistivity measurements and downhole temperature profiles.

The Haparangi Rhyolite at Wairakei is considered tentatively to be an intrusive rhyolite of late Huka age (Grindley 1965).

9.9.3 STRUCTURE

The Wairakei production field is located on a structural high situated between the major Taupo-Reporoa Basin to the east and a series of smaller block and basin structures to the west. Structure is largely controlled by a series of normal faults which strike northeast, parallel to the trend of the Taupo Volcanic Zone. Most of these faults are still active.

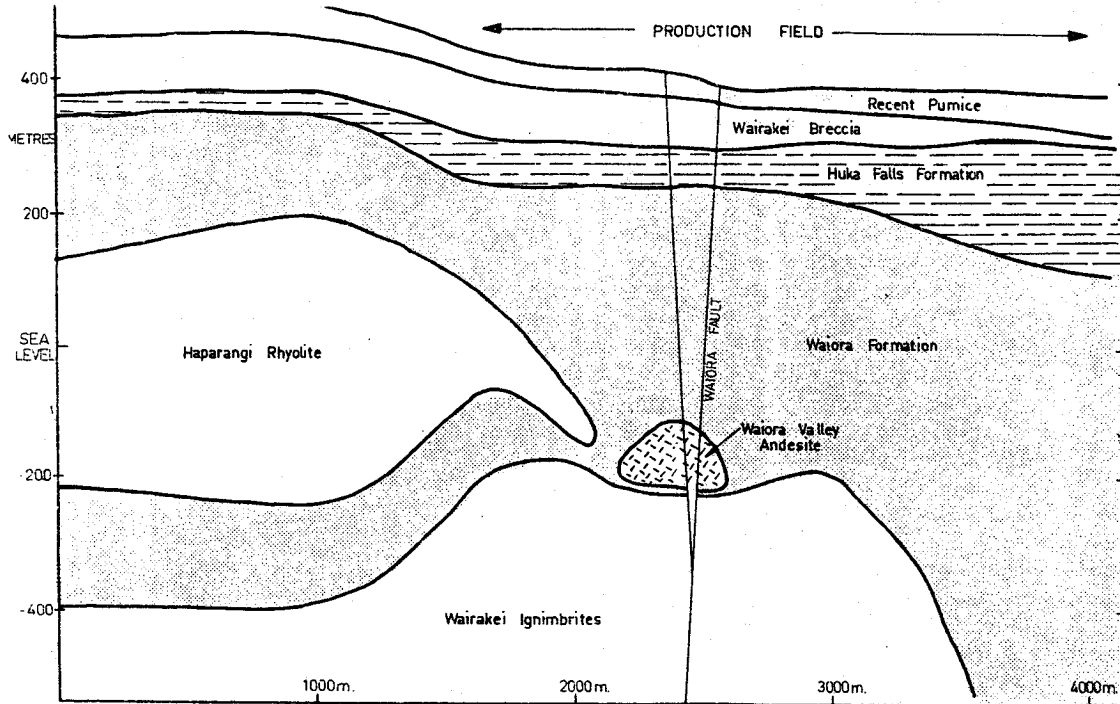


Figure 9.9.2 Cross section ABC through Wairakei geothermal reservoir showing geological structure. Vertical scale twice the horizontal scale.

9.9.4 ROCK PROPERTIES

Cores taken from investigation wells drilled into the hot water reservoir at Wairakei have been extensively tested for wet and dry bulk densities, particle density and porosity.

In 1975 Terra Tek Inc. conducted a series of comprehensive tests on selected cores from Wairakei for Systems Science and Software Inc. (Pritchett, 1977). Cores used for these tests had remained drying in the core shed for ten years before testing. Bulk density and particle density measurements agreed with those previously done on fresh cores. Results of these tests are tabulated below:

Table 9.9.1. Properties for Wairakei Hot Water Reservoir Rocks. Densities are tonnes/m³ and effective porosity per cent by volume.

Formation	Bulk density		Effective porosity	Grain density
	wet	dry		
Surface Pumice	1.88	1.39	49	2.71
Huka Falls Formation	1.99	1.59	40	2.70
Waiora Formation	2.02	1.64	39	2.72
Wairakei Ignimbrite	2.36	2.22	14	2.69

The linear coefficient of expansion for the Waiora Formation was found to be 8.2×10^{-6} m/m/°C and the dry specific heat 0.71 to 0.75 J/g°C. Thermal conductivity increased with increasing stratigraphic depth of the formation: measured values (saturated) were: Surface Pumice 1.03, Huka Falls Formation 1.28, Waiora Formation 1.56, and Wairakei Ignimbrite 2.11 W/m°C.

9.9.5 HYDROLOGY

The production field covers an area of 2 km² but this is only part of a much larger reservoir, as shown on Figure 9.9.1. Down to depths explored by drilling (1.2 km, and one well to 2.5 km) the Waiora Formation, a heterogeneous mixture of acid volcanic pyroclastics, vitric tuffs, sediments, and a rhyolite sill, forms the aquifer system from which geothermal fluids are withdrawn. A hot water reservoir (over 200°C) covering an area of 11 km² has been delineated by drilling and geophysical exploration.

At Wairakei 100 wells have been completed in the production area, 16 deep exploration wells in the hot water reservoir outside the production area and four deep and two shallower wells completed in the "cold" area outside the hot water reservoir.

Exploratory wells drilled outside the hot water reservoir have shown that there are hydrological connections between these "cold" wells and the hot water reservoir. Well 223, a "cold" well 5 km west of the production area, reacts almost immediately to changes in drawoff rate in the production field (Bolton, 1970). Bolton used the steep pressure gradients between cold wells and the hot water reservoir as evidence for some kind of low permeability barrier between the hot water reservoir and the surrounding cold water, down to depths of at least 1 km.

The Wairakei hot water reservoir is connected hydrologically to another hot water reservoir of about the same size located 8 km to the SE at Tauhara (Figure 9.9.1). This reservoir has not been exploited.

The intensive pattern of active, northeast-striking faults through the Wairakei reservoir is the major control on fluid flow. These faults penetrate the Huka Falls Formation "caprock" allowing the escape of hot fluids to feed natural thermal features, and when pressure conditions are suitable they may allow cold water from the surface water table to penetrate the hot water system. The faults also provide channels for vertical inflow of hot water into the aquifer system from below. Within the hot water filled aquifer system faults allow rapid propagation of pressure changes.

Thus the hot water aquifer system at Wairakei is unconfined, in that the "caprock" is penetrated by active faults and the same faults provide channels for inflow of hot water into the system from below. In addition, although there seem to be impermeable barriers around the hot water systems down to depths of at least 1 km, the cold wells located outside the hot water reservoir are affected by pressure change within the reservoir.

9.9.6 HISTORIC DEVELOPMENT OF MASS WITHDRAWAL

The withdrawal history from the Wairakei reservoir is shown in Figure 9.9.3. Output from the "western" wells includes all investigation wells located outside the production field and well 204 which blew out in 1960 and continued to discharge uncontrolled until 1973 when discharge ceased. Heat withdrawal from the production field is currently 1570 MW, and natural heat discharge is of the order of 400 MW (both relative to 12°C) - Current mass withdrawal rate is about 5500 t/h.

9.9.7 CHANGE OF PRESSURE IN THE AQUIFER SYSTEM

Average pressures at 152 m below sea level in the production field are plotted on Figure 9.9.3. Pressure changes due to withdrawal of mass and heat are discussed in detail by Bolton (1970) and Pritchett (1977). Bolton pointed out that the behavior of the Wairakei reservoir is primarily governed by the saturation pressure-temperature relation for water. Hydrostatic pressures throughout the reservoir have followed the trends shown on Figure 9.9.3. However, in the upper parts of the aquifer system below the production field a zone filled with saturated steam has developed. Pressure drop in this zone depends on changes in steam temperature.

9.9.8 LAND SUBSIDENCE

Surveys show an area of over 30 km² is subsiding at more than 10 mm/year (Figure 9.9.1). Within this area are two smaller zones each of about 1 km² which have subsided comparatively rapidly. The zone at Karapiti, 3 km south of the production field, was the most rapidly subsiding part of the survey network until about 1963, when the subsidence rate decreased to the same rate as for the surrounding ground surface. Subsidence at bench mark AA77 within this zone is plotted on Figure 9.9.4.

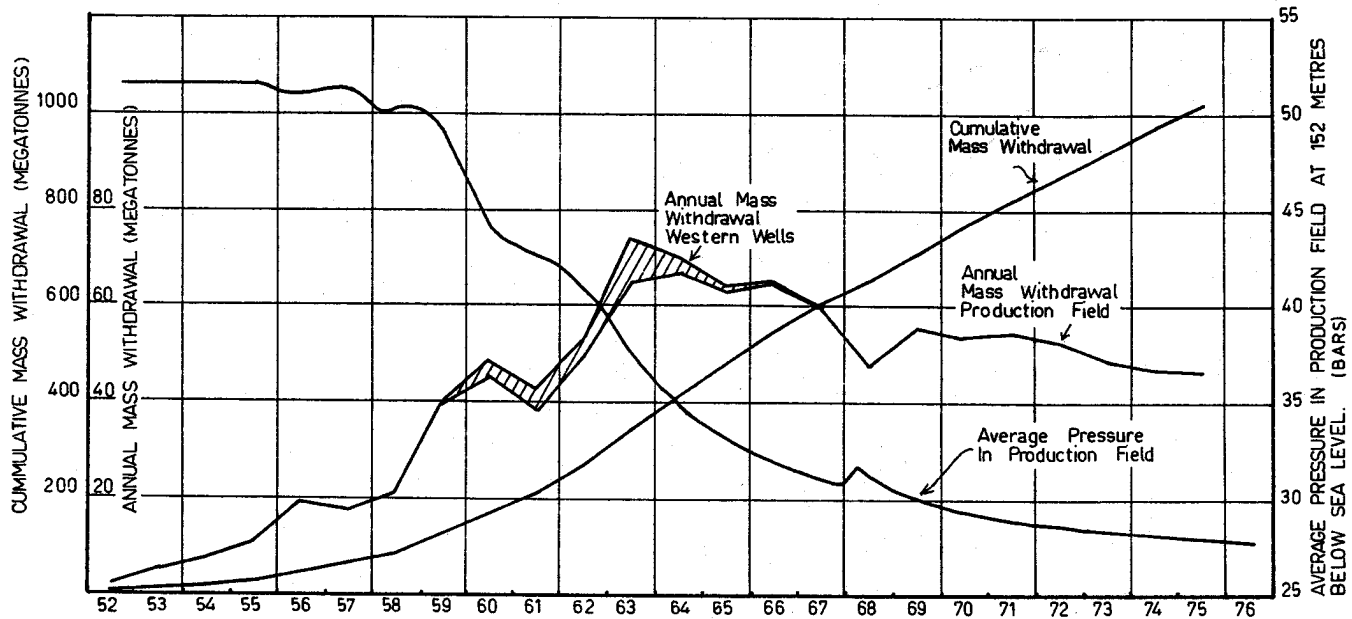


Figure 9.9.3 Wairakei hot water reservoir: mass withdrawal and aquifer pressure, 1952-1976. (Pre-1962 pressures after Bolton, 1970.)

About 1960 the subsidence rate at bench mark A97 began to increase and over the next few years the zone of rapid subsidence immediately north of the eastern production field shown on Figure 9.9.5 was delineated. Subsidence at bench mark A97 in this zone is shown on Figure 9.9.4. Subsidence of A97 between 1971 and 76 continued at 135 mm/year compared with 138 mm/year between 1966 and 71 as shown on Figure 9.9.4. Economic interest centres on this zone of subsidence as both the steam and waste water channels from the production field cross the subsiding basin. Bench marks in this zone are surveyed annually to third order standards.

Subsidence at bench marks AA8, at Tauhara, and AA15 to the west of the Wairakei production field are also shown on Figure 9.9.4.

9.9.9 HORIZONTAL MOVEMENT

The network which has been set up to measure horizontal movement at Wairakei has been described by Stilwell (1975), and Hatton (1970) showed the calculated and measured horizontal strain along the steam mains due to subsidence. The horizontal control network was re-surveyed in 1977 and vector directions shown by Stilwell were confirmed. Vector movement is generally toward the center of subsidence. Annual horizontal movement between 1968 and 77 was about 110 mm/year at a radius of 250 m from the centre of subsidence, decreasing to about 15 mm/year at 750 m radius.

9.9.10 CAUSE OF SUBSIDENCE

Subsidence in the area shown on Figure 9.9.5 must be related to the withdrawal of geothermal fluids. However, the more widespread subsidence as shown on Figure 9.9.1, although probably related to the underground hot water system, may be the result of natural events rather than withdrawal of fluids in the production area. Browne (1973) pointed out that at the Broadlands geothermal area (20 km NE of Wairakei) a natural rate of subsidence of 3.6 mm/year may have been occurring for the last 3400 years. Withdrawal of fluid at Wairakei has resulted in a number of continuing changes. The most significant of these is the overall lowering of hydrostatic pressures in the aquifer and the creation of a steam zone in the upper part of the aquifer in the production field. Computer modelling by Pritchett (1977) suggests that the gradual lowering of temperatures in this zone of saturated steam has been a major factor in controlling the

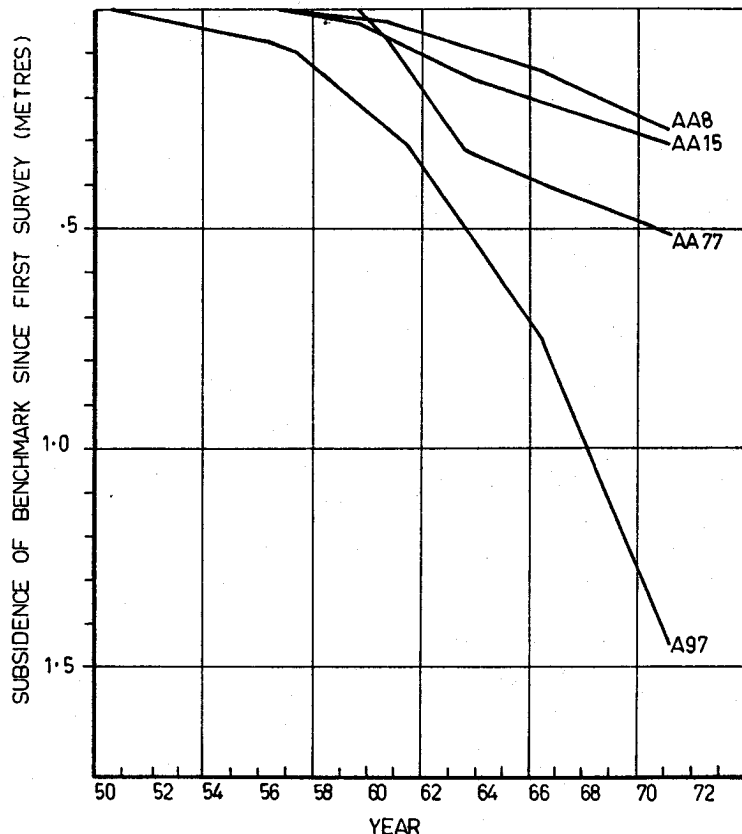


Figure 9.9.4 Subsidence at selected bench marks. For locations see Figure 9.9.1. Benchmark A97 first surveyed 1950, AA8 and AA15 1956, and A77 1959.

location and magnitude of subsidence. McNabb (1977) has suggested that pressure changes in the aquifer allowing cool surface water to penetrate fissures in the "caprock" and cool thick sections of underlying formations could account for the observed subsidence.

It is probable that the observed subsidence is the result of falling hydrostatic pressure in the deeper part of the aquifer system, falling steam pressure in the upper part of the aquifer and possibly the intrusion of cold water from the surface water table into the aquifer system. There has been no evidence of subsidence causing casing protrusion. Most casing strings are cemented into the Huka Falls Formation, thus the formation causing subsidence must lie below the Huka "caprock."

Hatton and Stilwell drew a correlation between the thickness of the producing aquifer (Waiora Formation) and the amount of subsidence.

9.9.11 ECONOMIC IMPACT OF SUBSIDENCE

The major structures affected by subsidence are the steam pipelines from the production field to the power house and the channels carrying separated geothermal water to waste. Differential subsidence has had no observed effect either on the power house or on ancillary buildings around the production field.

Both horizontal and vertical movement have occurred along the steam mains route. Maximum movement is near bench mark A97 (Figure 9.9.5), where horizontal movement is about 75 mm/year and vertical movement 130 mm/year. As the steam mains cross the edge of the subsiding basin, different sections are put in tension and compression (Hatton, 1970). Movement is accommodated to some extent by expansion loops which were built into the pipelines to allow for thermal

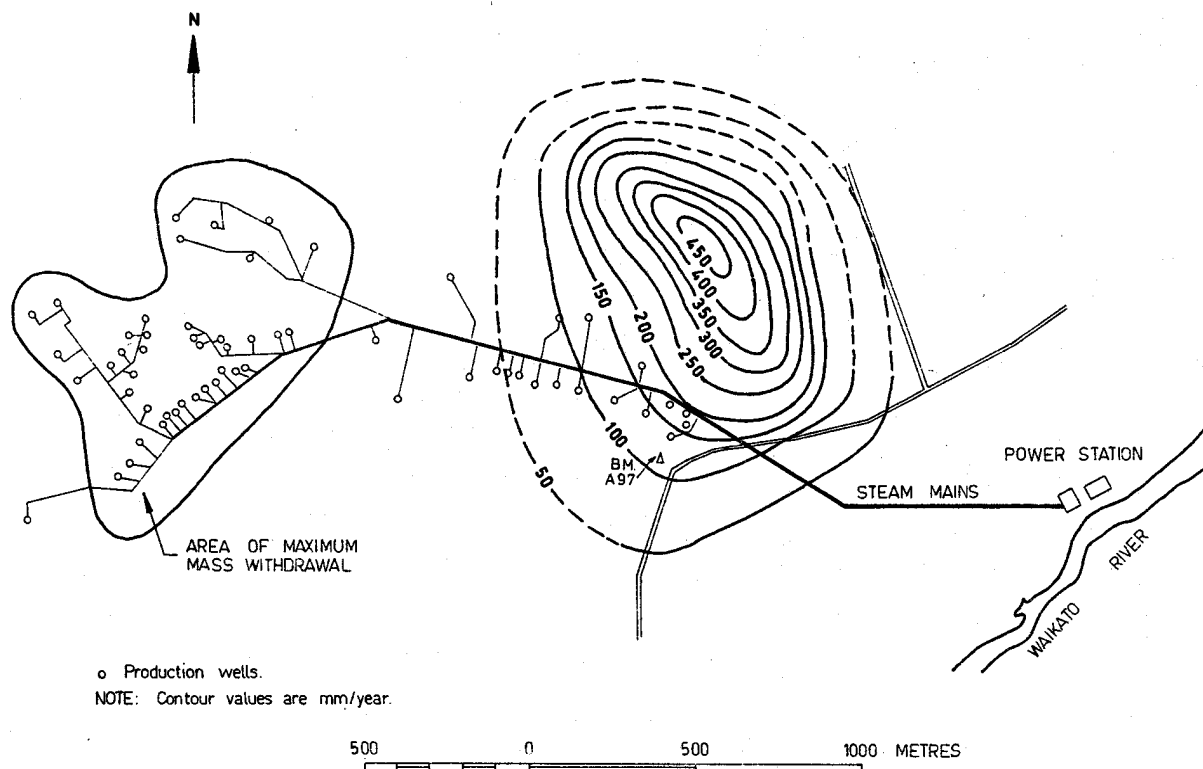


Figure 9.9.5 Subsidence rate in Wairakei production field, 1964-74. Redrawn from Figure 1, in Stilwell, Hall, and Tawhai, 1975, "Ground Movement in New Zealand Geothermal Fields," in Proceedings of Second U.N. Symposium on the Development and Use of Geothermal Resources: San Francisco, May 1975.

expansion. When these loops reach the limit of the travel, sections are either added or removed from the pipeline to restore the loops to their proper operating positions.

The waste water channels have a special sliding joint to allow movement between different sections of the reinforced concrete lining.

No measures are taken to control the rate or location of subsidence. Instead, the amount of subsidence and its effects are closely monitored in areas of economic interest and remedial action taken when installations are endangered.

9.9.12 ACKNOWLEDGMENT

The permission of Mr. N. C. McLeod, Commissioner of Works, to publish this paper is acknowledged.

9.9.13 REFERENCES

BOLTON, R. S. 1970. The behaviour of the Wairakei geothermal field during exploitation. *Geothermics, Special Issue 2*, pp. 1426-1439.

BROWNE, P. R. L. 1973. *Geology, mineralogy and geothermometry of the Broadlands geothermal field, Taupo volcanic zone, New Zealand*. Submitted for Ph.D. thesis at Victoria University of Wellington.

GRINDLEY, G. W. 1965. The geology, structure and exploitation of the Wairakei geothermal field, Taupo, New Zealand. *Bulletin, N.Z. Geological Survey*, 75.

HATTON, J. W. 1970. Ground subsidence of a geothermal field during exploitation. *Geothermics, Special Issue 2*, pp. 1294-1296.

MCNABB, A. 1977. Ground subsidence and reinjection. Internal report, Applied Maths Division, Department of Scientific and Industrial Research.

PRITCHETT, J. W. 1977. Geohydrological environmental effects of geothermal power production, phase IIA. Systems, Science and Software Report SSS-R-77-2998.

STILWELL, W. B., HALL, W. K., and J. TAWAHAI. 1975. Ground movement in New Zealand geothermal fields. Proceedings of second United Nations symposium on the development and use of geothermal resources.

Table 9.10.1 Aquifer characteristics

Aquifer	Location of tested well	Coefficient of transmissibility [m ² /hr]	Permeability [m/hr]	Storage coefficient
Bangkok	Bang Pun	160	3.40	1.00 x 10 ⁻⁴
Phra Pradaeng	Pom Phra	110	3.74	-
	Chun Navy Base			
Nakhon Luang	Phra Pradaeng	70	2.38	-
	Wat Phai Ngoen	120	2.38	1.00 x 10 ⁻⁴
	Wat Phai Ngoen	65	2.21	1.00 x 10 ⁻⁴
	Lum Phini Park	100	3.40	2.00 x 10 ⁻⁴
	Pak Kret	110	2.55	-
	Bang Bua	125	3.45	2.2 x 10 ⁻⁴
	Dept. of Mineral Resources	50	2.65	2.60 x 10 ⁻⁴

Table 9.10.2. Ground water pumpage for public water supply in Bangkok¹

Year	Pumping rate (m ³ /day)	Year	Pumping rate (m ³ /day)
1965	84,314	1971	331,966
1966	199,170	1972	318,276
1967	316,963	1973	362,738
1968	342,963	1974	370,032
1969	310,027	1975	350,000
1970	307,540	1976	345,000

¹Source of data: Bangkok Metropolitan Water Works Authority.

a