WAIRAKEI-TAUHARA, NEW ZEALAND: A TWO-PART STORY ON 60 YEARS OF GEOPHYSICAL MONITORING AND DIRECT GEOTHERMAL USE

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ABSTRACT

Wairakei power station has been generating for 60 years and direct use applications for even longer. The long history of geophysical monitoring at Wairakei-Tauhara, New Zealand, has helped understand the causes of many reservoir processes and environmental effects of large scale development. Monitoring studies included changes in: groundwater level, subsidence, heat-loss from surface thermal features, micro-gravity, and micro-seismicity. Each of these data-sets has revealed the effects of subsurface physical processes that accompany extraction and reinjection of reservoir fluid. When interpreted together with downhole pressure and temperature data, incorporating subsurface boiling processes, the geophysical monitoring datasets provide a valuable source of information that can assist in the calibration of models (reservoir simulation) improving forward projections of reservoir behavior under modelled development strategies.

In addition to power generation, the broader geothermal resources associated with the Wairakei-Tauhara Geothermal System have been supporting a wide range of direct uses. Examples are discussed, including the direct uses that have emerged through the period of the Wairakei power development, and the potential for expanded direct utilization from this energy resource. Careful reservoir management, informed by comprehensive monitoring has enabled reliable and sustainable resource use for both power generation and direct use.

Keywords: Wairakei, Tauhara, direct use, geophysics, monitoring, geothermal energy

1. INTRODUCTION

The paper discusses both geophysical monitoring and direct geothermal use, summarized from material prepared for the proceedings of the 2018 New Zealand Geothermal Workshop (Bromley et al., 2018 and Carey et al., 2018). Monitoring of the Wairakei-Tauhara geothermal system, near Taupo, in New Zealand (Figures 1a, 1b), has been an integral part of its development history for both electrical power production (currently 410 MWe operating capacity) and direct use (~1600 TJ/yr). A historical review of geophysical monitoring at the Wairakei / Tauhara geothermal fields was undertaken in 2009. This included papers on: subsidence (Allis et al., 2009, Bromley et al., 2009), gravity changes (Hunt & Graham, 2009), groundwater level changes (Bromley, 2009), and other geophysical investigations (Hunt et al., 2009), complemented by reviews on numerical modelling (O'Sullivan et al., 2009), reservoir physics (Bixley et al., 2009) and discharge chemistry (Glover & Mroczek, 2009). An update on these studies (Bromley et al., 2018), and joint interpretation of the observed changes, helps inform the ongoing analysis of reservoir performance, and provides investment planning confidence for long-term sustainable energy extraction.

The 60-year development history at Wairakei-Tauhara offers a unique opportunity to study the long-term physical response of a liquid-dominated reservoir subject to large net mass extraction. Monitoring of geophysical parameters since the start of production includes: ground levelling from 1955, ground-water level from 1955, surface heat loss from 1954, micro-gravity from 1961, and seismicity from the 1950's (DSIR/GEONET) augmented by a 13 station micro-seismic network from 2009.

Pressure, temperature, and saturation changes are parameters important to the underlying mechanisms that influence the geophysical responses. To illustrate this, the pressure history of various Wairakei aquifers hosted in Waiora Formation (WF) and mid-Huka Falls Formation (HFF) is shown in **Figure 1c**, and groundwater levels and southwest (SW) steam zone pressure history is shown in **Figure 1d**.

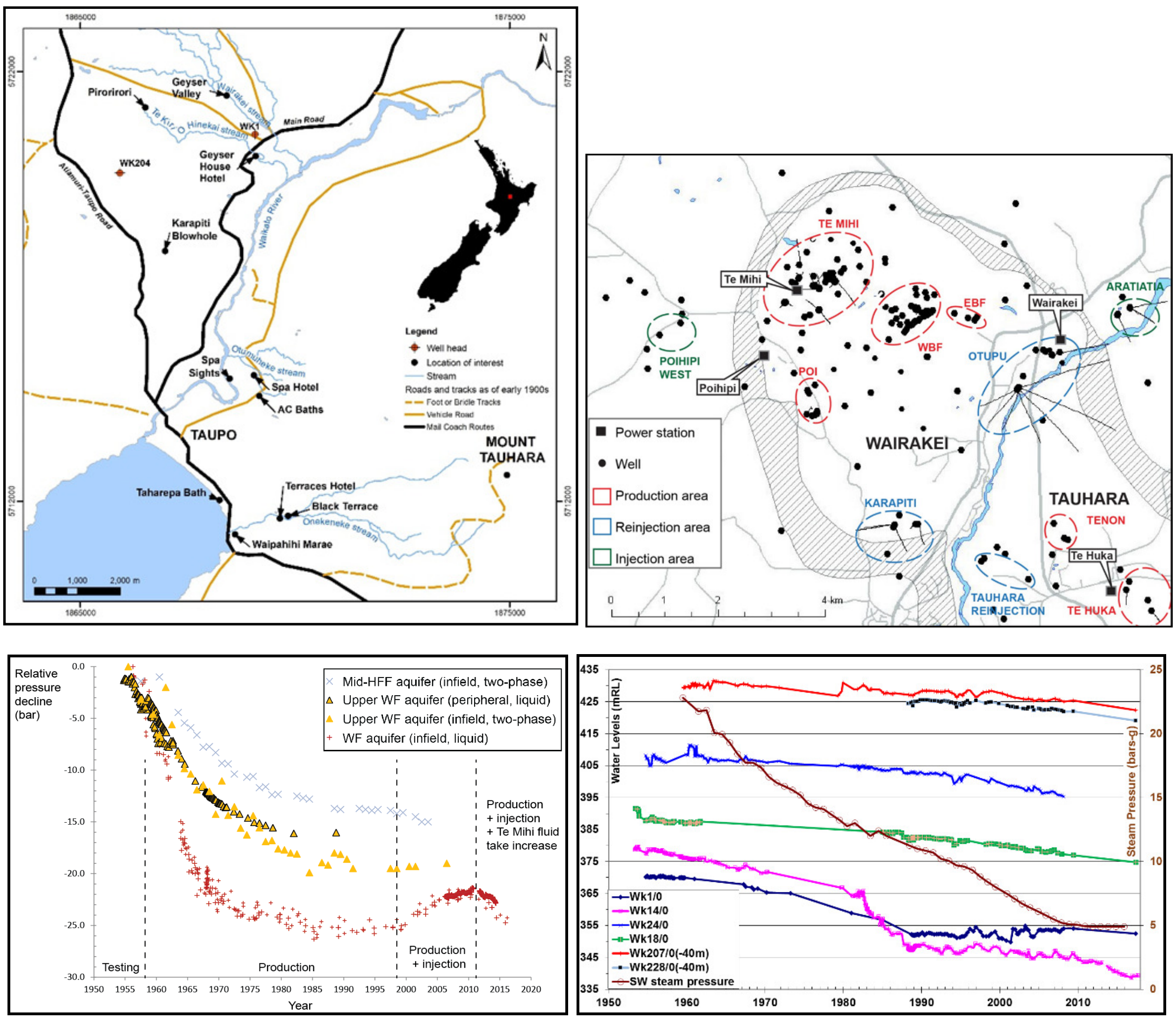

Figure 1 a) Location map of Wairakei-Tauhara, Taupo (~1900); **b)** Geothermal bore-fields (2018), power-stations and wells (EBF, WBF, POI = Eastern, Western & Poihipi Bore-Fields); **c)** Pressure changes in Wairakei aquifers (from Sepulveda et al., 2017), **d)** Groundwater level and SW steam pressure.

An integrated approach to modelling and interpretation is beneficial in linking the dynamic processes. For example, micro-gravity surveys are linked to ground and groundwater levels. The rock stress changes created by the thermo-mechanical effects of fluid movement (i.e. a mass change), interacting with tectonic and thermal stresses, influence micro-seismicity. Effective stress change also causes observable ground deformation, particularly in areas where the rock properties are anomalously weak (Bromley, 2018). Insights into field boundaries and reservoir structure can also be obtained from integrating geophysics with reservoir data (Sepulveda et al., 2014).

Direct use has been a feature of the Wairakei-Tauhara Geothermal System (**Figure 1a**) from since the time of the earliest Maori settlement (Severne, 1999). Subsequent Māori habitation near geothermal springs at Wairakei and Tauhara saw the resources provide for Hapu (extended family groupings) for heating and cooking. With the development of roads in the mid to late 1800's the area became more accessible for sightseeing, tourism, bathing and associated treatment of ailments. Various accommodation facilities developed. Much later, in the 1940's, the interest in energy development emerged, investigations were undertaken, and large-scale energy development for electricity generation began at Wairakei. Consequently, opportunities emerged for direct use of geothermal resources. These have included tourism, bathing, horticulture, aquaculture, and kiln drying of timber. As the town of Taupō has grown, in areas where geothermal fluids are present at a relatively shallow depth, the resource has been used for heating residential and commercial facilities. Looking to the future, there will be many opportunities to increase direct use of the abundant resource. This will be in partnership with electricity generation, being sustainably managed through appropriate policy and sound resource monitoring.

2. MONITORING

Since the 2009 review, ongoing geophysical monitoring data from Wairakei and Tauhara have been collected, interpreted and discussed. The following subsections give an overview of the results of updates on: groundwater level, subsidence, surface heat-loss, micro-gravity and micro-seismicity.

2.1 Groundwater-level

Groundwater levels have been monitored dating back to 1955. An update of selected plots of water level changes is presented in **Figure 1d**. Alum lakes area (NW of WBF, **Figure 1b**) experienced an anomalous period of groundwater level decline (up to 5m between 1999 and 2001) which culminated in a local hydrothermal eruption (Bromley & Clotworthy, 2001). A downflow resulting from reduced shallow steam-zone pressure was postulated as a mechanism. Nearby monitor bores (e.g. WK207/0 and WK228/0) show a continuing, but gradual, water level decline in the surrounding area, suggesting that the effect of the localized Alum Lakes downflow has not yet stabilized. Ground water levels near the WBF, represented here by WK24/0 and WK18/0, have experienced an accumulated decline of about 15 m. The rate of decline accelerated between 1980 and 2005, but has since steadied. The largest water level declines occurred at the border between EBF and WBF (WK14/0), with up to 40 m measured, at a rate that accelerated between 1982 and 1989. This is thought to have been a temporary response to local casing failures in production bores allowing increased downflows of groundwater into the reservoir through the wells before they were cemented up (Bixley et al., 2009). WK1/0 and nearby E/0 in the EBF, show 18m of decline by 1989, then the water level stabilized at about the same elevation as the subsidence pond that had developed in the Wairakei stream (**Figure 1b**, east of the EBF). This is interpreted to indicate that the pond locally controls ground water levels, where shallow permeability is high, and recharging stream water now flows westwards, back towards the groundwater level depression near WK14/0.

In the Poihipi West outfield injection area (**Figure 1b**) groundwater monitor bores reveal decreases in water level of up to 7.6m between 2009 and 2017. This reflects a gradual return to normal water levels following the closure of the Poihipi condensate injection bore WK680 which had previously been linked to gradually rising groundwater levels of a similar amplitude, over the period that injection had been undertaken. At Tauhara, water levels have remained relatively unchanged since the previous summary (Bromley, 2009), with rainfall variations providing an explanation for <±1m changes. Importantly, there is no evidence of significant water level changes near Tauhara subsidence bowls or micro-gravity anomalies.

2.2 Subsidence

Recent subsidence studies (repeat levelling history, modeling and interpretation) have been presented in Bromley et al. (2013), Koros et al. (2016) and Sepulveda et al. (2017). A plot of rate changes with time at key benchmarks near the centers of four local subsidence anomalies (Wairakei, Spa, Rakaunui, and Crown) is shown in **Figure 2a**. Accumulated subsidence of more than 1m has occurred across a large proportion of the area of the Wairakei-Tauhara system. This is the result of the wide-spread pressure drawdown in the production aquifers which has, with time, diffused slowly up into the shallower clay cap rocks. These clays consist of layers of highly compressible, low permeability and hydrothermally-altered mudstone aquicludes (especially the Upper- and Lower-HFF).

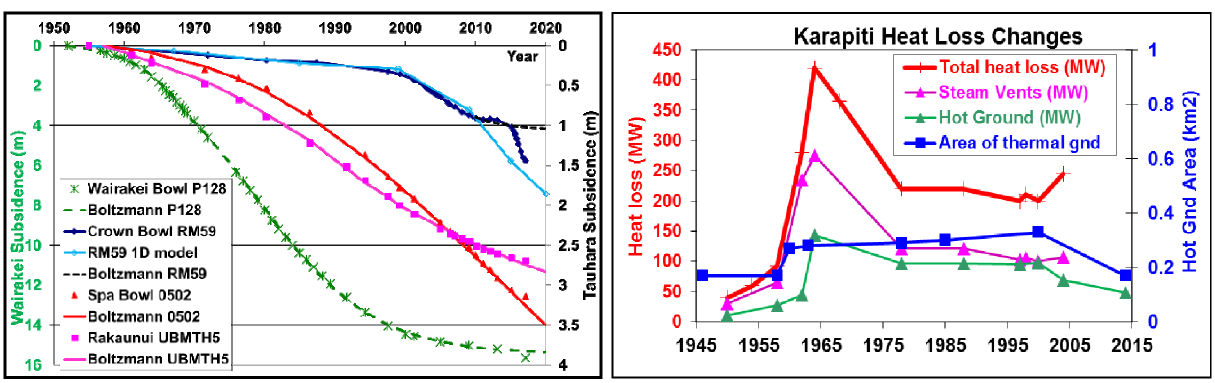

Figure 2 a) Subsidence level change history near centers of bowls; **b)** Karapiti surface heat loss changes.

In a few quite specific locations, such as at the Wairakei Bowl (adjacent to Geyser Valley and NE of EBF, **Figure 1b**), Spa (south of Tauhara reinjection sector), Rakaunui (north of Te Huka Power-station) and Crown Road (south Tauhara), the presence of thicker and shallower layers of yielding hydrothermal clays, at depths between about 50 m and 300 m, has resulted in greater subsidence, accumulating by January 2017 up to 15.6 m, 3.1 m, 2.7 m and 1.4 m, respectively (**Figure 2a**). In almost all cases the subsidence rate history follows a smooth curve that can be fitted with sigmoidal (Boltzmann) functions. The observed subsidence at Crown bowl (RM59) is better predicted by a 1D model accounting for pressure trends and a transition to non-linear yielding at different depths at different times. Subsidence modelling efforts are on-going using coupled TOUGH2 and ABAQUS software. Non-linear yielding mechanisms for the weakest mudstones/clays have been simulated using a 'Modified Cam Clay' approach (eg. Koros et al., 2016).

2.3 Surface heat-loss

Monitoring surface heat-loss is important for quantifying changes in the surface environment as well as for providing input for reservoir simulation modelling. An overview of Wairakei-Tauhara heat-loss (Hunt et al., 2009) incorporated learnings from a series of studies undertaken at Karapiti, and Bromley et al. (2011) documents studies that have improved the accuracy of the monitoring methods and the data capture at both Karapiti and across Tauhara. **Figure 2b** plots heat loss over time at Karapiti.

Repeat measurements of steam-vent discharges have not been undertaken since 2004 (for safety reasons). However, a gradual decline is inferred in total surface heat loss from Karapiti over the past 15 years from the observation of reduced sizes of steam clouds at the larger fumaroles, reduced area of hot ground from thermal infra-red surveys, increased vegetation density and height (as shallow ground temperatures cool), and reducing ground temperatures at repeat measurement sites. This decline is consistent with the observed history of a decline in the pressure in the underlying SW steam zone (**Figure 1d**).

2.4 Micro-Gravity

Repeat microgravity surveys across the Wairakei-Tauhara system have been conducted at regular intervals since the 1960's. These monitor the effects of changes in net mass caused by fluid extraction, reinjection, and recharge. Such micro-gravity changes are strongly influenced by the effects of density changes in 2-phase zones, where boiling from pressure decline causes steam saturation increase, or where liquid recharge (e.g., from injected fluid, upflow, downflow or lateral inflow) causes liquid saturation increase. The results of repeat surveys of Wairakei (1961 to 1991), are given in Hunt (1995), while Hunt & Graham (2009) summarize the gravity change observations and interpretations from repeat surveys of Tauhara (1972 to 2006). Subsequent Wairakei - Tauhara micro-gravity surveys were conducted by GNS Science in 2009 and 2017 for Contact Energy.

At Wairakei, the initial response to pressure decline and boiling between 1958 and the 1970's was a large gravity decrease across the borefield areas, indicating density decrease from expansion of the steam-zones. This was later followed by gravity increases: NE Geyser Valley in the 1970s, EBF in the late 1970s, WBF in the late 1980s, Te Mihi and SW of WBF in the early 1990s (Hunt, 1995). Increases typically result from liquid re-saturation of pores and fractures from increasing deep liquid pressure in 2-phase dominated zones. However, the onset of gravity increases preceded the onset of deep pressure increase, which only became pronounced when reinjection increased between 1999 and 2011 (**Figure 1c**). This observation is consistent with the hypothesis that much of the recharge water was originating from the groundwater above the steam zone rather than from rising brine levels from below. The history of groundwater level changes (section 2.1) is consistent with this hypothesis.

At Tauhara, by 1966, reservoir pressure changes transmitted from Wairakei had already caused localised boiling, net mass loss and gravity decline. From 1985, gravity in parts of northern Tauhara also started to increase as liquid recharge began to re-saturate the steam-dominated boiling zones.

The latest micro-gravity changes, 1994-2009 (15 years) and 2009-2017 (8 years) show that both periods were dominated by gravity increases, implying net mass increase from liquid recharge. For 1994-2009, a large positive anomaly (>160 μ gal/10 yrs) was distributed across all the Wairakei borefields (Eastern, Western and Te Mihi sectors). Another positive anomaly (>100 μ gal for 2006-2009) was observed in northern Tauhara. Since 2009, the positive anomaly over Tauhara has intensified and broadened to the south, while the one over Wairakei has reduced to a minor negative anomaly (-20 μ gal/10yrs) centered over the Te Mihi production sector. These observations are consistent with re-saturating liquid influencing the HFF at Tauhara, and increased boiling due to additional production pressure drawdown, since 2011, in the Te Mihi sector. Numerical integration of the gravity changes and application of Gauss's theorem across the entire geothermal system implies net mass gain over the 2009-2017 period of 114 Mt ($\pm$ 20%). Total production was 719 Mt and injection 403 Mt, resulting in a net mass loss of -316 Mt. Therefore, induced fluid recharge is calculated to be about 430 Mt, or about 52 Mt/yr. Over the previous 1994-2009 period, an induced recharge at Wairakei of 705 Mt, or 47 Mt/yr, is similarly calculated. The mass increase across the Tauhara anomaly (2006-2009) was 24 Mt (8 Mt/yr). Consequently, the total mass recharge rate across Wairakei - Tauhara has remained steady since 1994 at about 52-55 Mt/yr (Bromley et al., 2018).

2.5 Seismicity

As part of Contact Energy's monitoring program at Wairakei, GNS Science operates three seismic stations through the GEONET network to detect relatively large seismic events (nominally M>1.5) and IESE Ltd operates a local Wairakei Seismic Network, (WSN) to monitor micro-earthquake (MEQ) activity. The WSN uses 13 downhole seismometers installed at depths ranging up to 1,100 m. The downhole instrumentation has improved the sensitivity of detection; with the Magnitude of Completeness (Mc) of the WSN estimated at Mc = 0.2. The MEQ hypocentre distribution at Wairakei can be broadly grouped into shallow (<4 km) and deep (4-7.5 km) events. Shallow MEQs are within the DC resistivity boundary whilst deep MEQs are preferentially offset to the north-west; see **Figure 3** (Sepulveda et al., 2016). Both 'near'-injection and 'near'-production seismic activity has been detected by the WSN since 2009 and this activity tends to form recurrent patterns which are described below and shown in **Figure 3**.

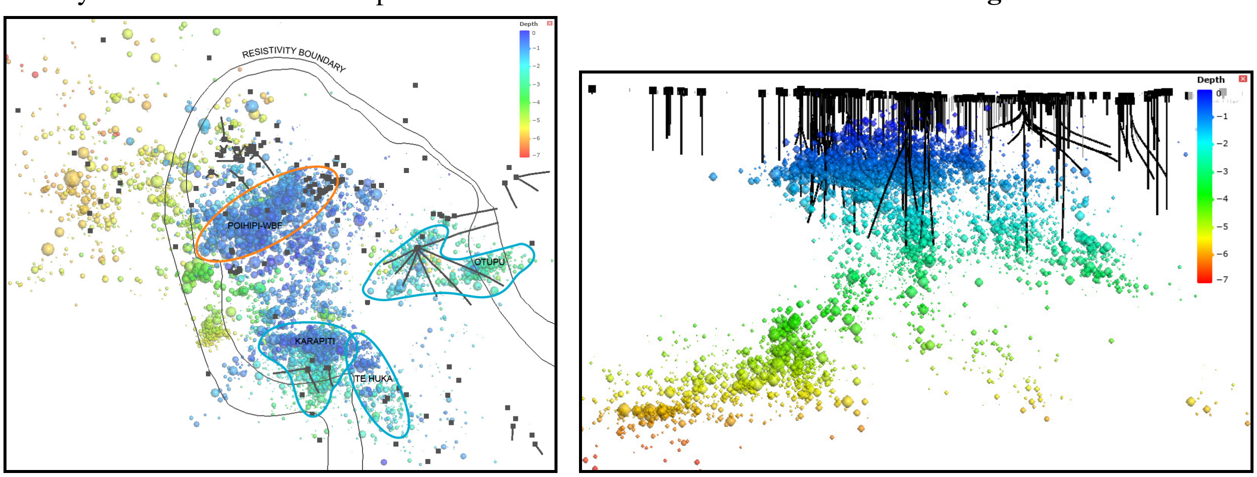

Figure 3 a) Wairakei seismicity map (period 2009-2017) showing clustered seismicity; **b)** View from the south. Dot size is proportional to magnitude and color proportional to depth (from Bromley et al., 2018).

'Near'-injection activity occurs in clusters near Otupu, Karapiti and Te Huka injection sectors. 'Near'-production activity forms a SW-NE striking band between Poihipi power station and the WBF. This constitutes the most seismically active area of the Wairakei field. Deeper seismicity appears to delineate a hot-fluid recharge conduit beneath the Te Mihi production sector. Regardless of the specific physical mechanism triggering induced seismicity (e.g. pressure changes, thermal stress), shallow MEQs tend to cluster at some distance from wells, indicating geological structure and fluid flow as factors controlling the hypocenter locations.

3. RESERVOIR PROCESSES

Good reinjection management is crucial to sustainable energy extraction, whether for power generation or direct use. Although such management is often focused on minimizing adverse effects from reinjection returns, it is also important to understand and manage the effects of changing pressure on boiling of up-flowing recharge fluid. As well as influencing the fluid and gas chemistry (e.g. CO_2 content), some geophysical changes are caused by interacting fluid and rock properties (e.g. density, porosity, local stress state, strain rate, and fracture permeability). A physical process model is needed to interpret such changes.
Geophysical monitoring datasets provide a valuable source of reservoir change information that can assist in the calibration of reservoir simulations, and improve projections of reservoir behavior under extraction-injection strategy scenarios. The geophysical data is interpreted together with downhole data on pressures, temperatures and 2-phase saturation conditions, and then modelled as an integrated package. This has been particularly relevant to the recent reviews of the nature of the connectivity between south Wairakei (Karapiti) injection and Te Huka (Tauhara) injection. The seismic activity at depth in this part of the field suggested greater permeable connection in the numerical model than previously captured. The adjustment of deep permeability in this area of the model is helping to improve pressure matching in the numerical model which is important when considering long term reservoir changes in response to injection.

4. DIRECT USE

The earliest recorded uses at Wairakei-Tauhara are of Māori using the resources to provide warmth, bathing, healing, places to cook and supplies such as fern root, black dye and red ochre. **Figure 1a** shows areas where geothermal water was readily accessible. In the colonial era, several thermal hotels were built near Taupo. In 1873, at the junction of the Otumuheke stream with the Waikato River, a visitor described a natural channel providing a nice slide into the thermal pool below. This area (upgraded in September 2018) remains very popular for 'au-naturale' free bathing today. By 1885, the nearby Spa Hotel, had 5 hot or tepid baths for paying customers. The upstream AC Baths facility was named after the Armed Constabulary, whose soldiers dug the original pool in the 1880's. It has developed into the Taupō District Council run AC Baths facility (**Figure 4a**). A pool in the grounds of the Geyser House Hotel (now Wairakei Resort Hotel) and several pools in Te-Kiri-o-Hinekai stream nearby were developed in 1881. The "Terraces" Hotel was built in 1889 above Onekeneke valley of silica and hot pools. It was renamed Debretts Thermal Hotel in 1964 and the thermal valley is now known as the Taupō DeBretts Spa Resort.

During the late 1940's geothermal investigation drilling at Wairakei identified a significant heat resource. By 1950, one of the earliest wells, WK1 (183 m deep), was being used to supply steam (14 bars WHP) for direct heat use at the Wairakei Resort Hotel (Cooking in the kitchen, facilities heating and pool heating). In the late 1950's, WK1 was replaced with steam supplied from a pipeline feeding the Wairakei Power Station. Today, piped geothermal steam is used to heat buildings, two swimming pools, and outdoor hot tubs. The Wairakei Power Plant was commissioned in 1958 and the pioneering geothermal development became a feature of hotel-organized tours. A drilling incident at WK 204 (near Poihipi, **Figure 1b**) in 1960 saw the creation of the "Rogue Bore". Between 1968 and 1973 tourist visits were organized to this spectacle, where the uncontrolled discharge caused the ground to shudder under your feet.

The Huka Prawn Farm next to Wairakei Power Station was developed as a geothermally-heated aquaculture business in 1987 by Aquatech Farms Ltd. By December 1988 there were about 150,000 Giant Malaysian River prawns growing in the outdoor ponds. Initially the farm used hot water taken from the Wairakei stream as a source of heat to raise the temperature of the freshwater circulating through the rearing ponds. The farm enlarged in 2002, adding 9 outdoor rearing ponds. As the Wairakei Power Station began injecting more geothermal water, the heat available from the Wairakei Stream decreased and the Pawn Farm moved to using heat taken from the reinjection pipeline (~90 ^{o}C). A tourism focus around the prawn operation developed with the rebranded Huka Prawn Park. Some 75,000 visits per year are made to Huka Prawn Park to tour the hatchery and rearing ponds, fish for prawns in the outdoor ponds, paddle boats, or enjoy a meal in the restaurant.

The Wairakei terraces were developed in 2000 using water supplied from the Wairakei geothermal field injection line. The banks of the stream were revitalized, walks established, the Honeymoon pool (Avenue bath) was dug out, a geyser and silica terraces established, and bathing pools constructed. The terraces have become coated in silica from the geothermal water cooling as it flows over them. Bathing pools have become popular for soaking and soothing the body in the silica-rich geothermal water. About 90,000 visitors per year visit the Wairakei Terraces (**Figure 4b**).

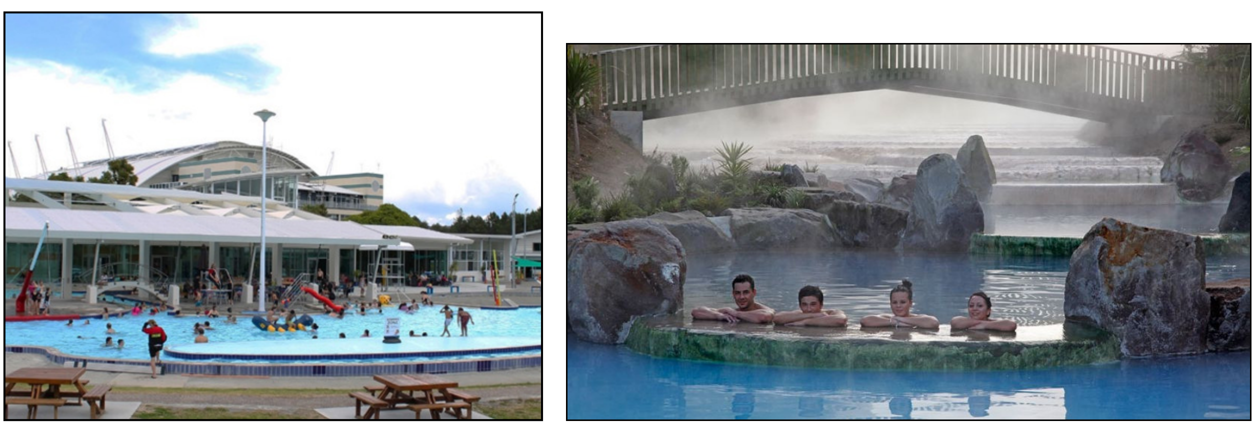

Figure 4 a) AC Baths; **b)** Wairakei Terraces pools.

Other Wairakei thermal tourism ventures include: the Wairakei Steamfield lookout, the Wairakei Thermal

Valley and its historic Geyser-Valley walkway, Helicopter Adventure Flights over the borefield, and Karapiti (Craters of the Moon) thermal area walkway. Novel direct geothermal heat uses at Wairakei include the Karapiti visitor kiosk (heated floor, see **Figure 5b**), and Wairakei international golf-course club-house (a 20 kW heat pump extracting heat from a man-made water hazard).

At Tauhara, steam from a well drilled in 1966 (TH2) has been used for decades to heat nursery beds at the Native Plant Nursery. In 2006, the nearby Tenon Taupō timber-processing facility transitioned from natural gas-fired boilers and timber-drying kilns to geothermal energy (Dobbie & Moore, 2011). The three 2-phase geothermal heat-exchangers that make up the heat-plant are shown in **Figure 5a**. Two heat-exchangers (HX 1 and 2) supply 180 ºC fluid and HX 3, 150 ºC fluid. Tenon thereby reduced its CO_2 emissions by about 28 kt/yr, reduced operating costs by NZ$ 1.2 M/yr and increased the existing kiln drying capacity by about 5%.

Figure 5 a) Tenon 2-phase geothermal heat plant; b) Karapiti visitor kiosk : geothermal floor heating.

In 2010 the Taupō Hospital transitioned from coal fired boilers to a geothermal energy supply. Geothermal fluid at 100 ºC is pumped from a 220m deep well, supplied to the hospital heat-plant heat-exchangers and then returned underground at 80 ºC. The downhole submersible pump supplies a peak of 400 kW of heat, and the average heat use over a year is about 200 kW (Febrianto et al., 2013). Greenhouse gas emissions from the hospital reduced by about 700 t CO_2 e/yr.

There have been several commercial horticultural ventures using geothermal energy to assist with production. Geotherm Exports grew phalaenopsis orchids in greenhouses on Tukairangi/Poihipi Road from 1981 until about 2006. 250,000 orchids were grown in the 8100 m^2 of greenhouse set up to mimic a tropical environment. 700 kW of geothermal heat was required at times of peak demand in winter (Koorey, 1996). Numerous shallow bores in the Tauhara area tap into a shallow geothermal resource (heated groundwater or steam) that is used to provide space and water heating for private dwellings, commercial/industrial properties, and accommodation facilities. In the industrial area (around Miro and Manuka Streets), concrete floor slabs are naturally heated by the warm (steam-heated) ground. Taupō motels and hotels utilize the shallow geothermal resource to provide heating to their facilities and water for private thermal pools from a mix of artesian wells, pumped wells and downhole heat exchangers.

In the future more can be undertaken to utilize directly the geothermal resources of the Wairakei-Tauhara geothermal system. An approach, along with a Medium Density Fibreboard manufacturing example, is detailed in Climo et al. (2017). In December 2017, a Geothermal Business Development Lead, was funded by the Bay of Connections, for a period of two years to accelerate the uptake of new businesses establishing using geothermal resources. Contact Energy has been working on several projects including timber processing and aquaculture. The co-location of plantation forestry and geothermal resources is a significant opportunity. Tourism is also a key business sector for New Zealand and is growing rapidly. Tourists are attracted to the globally-unique volcanic and geothermal environments which offer a range of experiences. The growth in this sector and visitor experiences can be significantly enhanced with the industrial and natural experiences on offer at Wairakei - Tauhara.

5. CONCLUSIONS

- Throughout the period of the Wairakei development there has been significant development of geophysical monitoring techniques. These have contributed to improved understanding of the resource, and enabled enhanced production-injection strategies for sustainable energy extraction.
- The geophysical monitoring datasets assist in the calibration of models (reservoir simulators), improving forward projections of reservoir behavior under modelled development strategies.
- Direct use of the geothermal resource has been a feature of Wairakei – Tauhara for many decades, with much promise for more up-take in the future.

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