EFFECTS OF REINJECTION AT WAIRAKEI GEOTHERMAL FIELD

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Keywords: *Wairakei, Geothermal, Reinjection Effects, Pressure Response, Production Chemistry, Recharge.*

ABSTRACT

For the first 46 years of operation, the Wairakei Geothermal field was operated without any significant reinjection. Over this time 2,000 Mtonnes of reservoir fluid was extracted and the deep liquid pressures, which had declined by 25 bar from the pre-development value, had been stable since the mid-1970's. Production well chemistry indicated that prior to reinjection, enhanced recharge, primarily hot, provided the fluid required to sustain reservoir pressures. Large scale reinjection commenced in 1998 and since then the deep liquid pressures have increased by 4 bar. Over the same period some uncharacteristic changes have been observed in production areas. In some liquid-fed production wells the feed temperatures have risen and in others the total gas content has more than doubled. Calcite scaling, which had not been previously observed, has become common in some production areas with a resultant accelerated production decline. These changes are thought to be associated with variations in the amount of boiling occurring in the deep, hot recharge plume as the system responds to changes in production and reinjection.

1. INTRODUCTION

Fluid extraction at Wairakei started soon after 1950 and continued for the next 46 years without significant infield reinjection. Prior to commencing large scale reinjection all extracted geothermal fluid was discharged to the Waikato River Although the deep liquid pressures initially declined quite rapidly, by 1980 the field pressures had stabilised to about 25 bar below the pre-development value (**Figure 3(a)**). Reinjection commenced in 1998 and over the next few years, as expected, there was an increase in reservoir pressure. However, there were some unexpected changes observed in the production wells. Some of the liquid-fed production wells showed a small increase (1ºC-3ºC) in feedzone temperature, together with large increases (in CO_2 content and changes to the previous chloride trends. In line with the large increases (around 10 mmol/100mol) in CO_2 several wells which previously had not shown signs of scaling began to form calcite scale, requiring workovers to mechanically remove the scale and maintain production. In this paper the monitoring results from four production wells, considered to be representative of the Western Borefield production area (**Figure 1**) are discussed. These are liquid-fed wells, each with a production history of more than 50 years.

For this study the data up to mid-2010 has been considered. This includes the initial production period from 1950-1998 with no infield reinjection, and the 1998-2010 period when there was little change in fluid extraction rates and partial reinjection of 30% of production was focused in the Otupu area (**Figure 1**). After 2010 fluid extraction rates were significantly increased and a new reinjection area at Karapiti South was commissioned, which together have changed the pressure distribution in the liquid reservoir. Mass extraction increased and portion of injection also increased. The amount of extracted fluid discharged to the river was subsequently reduced.

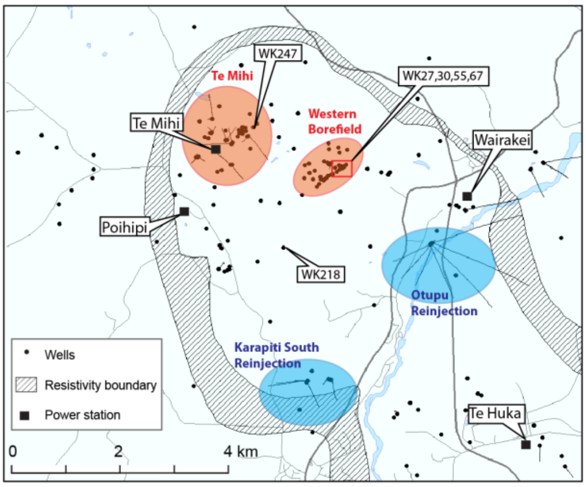

Figure 1: Wairakei Geothermal Field showing the location of the four wells used in this study as well as the major production and reinjection areas discussed.

2. RESEVOIR EVOLUTION

Before development, the natural heat flow due to surface activity at Wairakei consisted of about 400MWth of water and steam-heated features (Allis, 1981). The early well data indicated that boiling point-for-depth conditions were present down to about 400m below the surface with maximum temperatures of about 265°C (Banwell, 1957), which infers the mass recharge into the system was about 400 kg/s.

Under exploitation, the deep liquid pressures initially declined rapidly (**Figure 3(a)**), resulting in widespread boiling and development of a two-phase zone. The two-phase zone subsequently segregated into a vapour-dominated zone extending across much of the productive part of the resource. Western Borefield production wells, with their feed zones located below the boiling level, continued to produce from liquid conditions with enthalpy following a trend just below the liquid saturation temperatures. Up to about 1970 the feed temperatures declined in line with reservoir pressure decline, following a trend controlled by the saturation temperature – with the implication that boiling elsewhere in the reservoir was controlling the liquid temperature in the Western Borefield. After 1970 the feedzone temperature declined more slowly (about 0.3°C per year from 1970 to 1995) controlled more by dilution from shallower, cooler fluids (Glover & Mroczek, 2009).

Proceedings 36th New Zealand Geothermal Workshop
24 - 26 November 2014
Auckland, New Zealand

2.1 Enhanced Recharge

Brown et al. (1988) modelled the mass and chemical flows in the Wairakei field to determine changes in recharge with time using the schematic model shown in **Figure 2**. The model indicates that up to 1996 around 80% of the fluid produced was being replaced with deep high temperature recharge and the remaining 20% was derived from cooler low chloride fluids. These low chloride recharge fluids have been identified in shallow-cased wells in the production area and there is also likely to be a contribution from low chloride fluids migrating laterally into the reservoir across the boundary zone. The enhanced deep recharge was about 3 times the natural rate seen prior to field development.

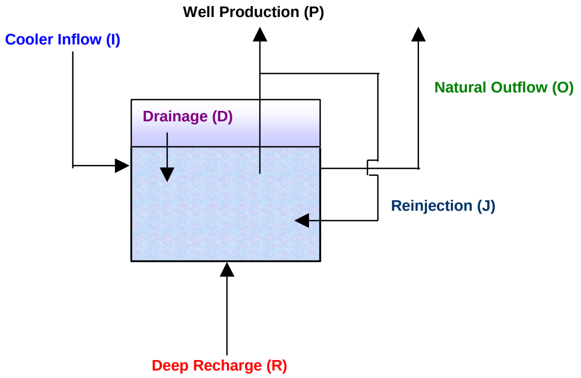

Figure 2: Schematic model used to calculate mass balance using chloride flux (from Glover and Mroczek, 2009).

Recent development drilling has shown the deep recharge source lies toward the northwestern part of the field (Te Mihi) where temperatures of more than 270°C have been encountered.

2.2 Pressure Change

Pressure change in the liquid reservoir, together with fluid extraction and reinjection rates from 1950 to 2010 are plotted on **Figure 3(a)**. For this plot only the pressures measured in the wells used in this study are shown. Until 2010, most of the other wells within the productive part of the Wairakei field follow the same trends within about 1 bar.

Before reinjection started, the liquid pressures were stable, declining by about 1 bar from 1973-1998 (**Figure 3**). Significant reinjection started in the Otupu area in 1998, gradually increasing with time, but generally maintained at about 30% of the total fluid extraction rate. As a result of reinjection, pressures increased evenly throughout the Wairakei liquid reservoir, with a total increase of 4 bar by 2010.

3. WELL MONITORING INFORMATION

3.1 Feedzone Temperatures

Feedzone temperatures have been monitored in many of the liquid-fed Wairakei production wells by making regular pressure-temperature surveys with the well in flowing conditions using standard downhole measurements tools (up to 1993 Kuster KT and KPG mechanical gauges with an absolute accuracy about ±2°C were used and after 1993 various electronic instruments with accuracy about ±1°C were used). Results of these surveys for the four selected wells are plotted on **Figure 3(b)**. Disregarding the initial rapid decline of the liquid feedzone temperature, from 1970 to 1998 prior to reinjection, the liquid feedzone temperatures were slowly declining at about 0.3°C per year

After 1998 (when reinjection began) the temperatures exhibit a small increase of about 1ºC to 3°C – or at least, the previous declining trend was arrested.

3.2 Calcite Deposition

Up to 1999 calcite scaling in the production wells at Wairakei had never been a serious problem. Prior to 1960 two of the Western Borefield wells had required cleanouts to remove calcite scale, but from 1960 to 1999 calcite scaling was not observed in any of the production wells. After 1999 accelerated decline in flow rate was observed in a few wells, and by 2005 eight wells were being affected by scaling, requiring workovers on approximately 2-yearly intervals to maintain production. The decline rates also accelerated in later years because the effective well opening had also reduced (as a result of the scaling). Of the wells discussed here WK27 and 67 were affected by calcite scaling and WK30 and 55 were not affected.

3.3 Reservoir Chloride

Before any deep wells had been drilled into the recharge area, the geochemical data indicated the deep liquid recharge had a Cl content of 1700 mg/L (Brown et al, 1988). Since 2005 eight production wells deeper than 2000m have been completed. The deepest of these has its main feedzone at 2300m with temperatures of 258°C and Cl 1630 mg/L. In 2013 additional deep wells were drilled which encountered feedzone temperature 270-272°C. Correspondingly higher reservoir chloride values are expected in these wells, but to date they have not been flowed for sufficient time to obtain reliable chemistry data.

Reservoir chloride values of about 1600 mg/L, measured in Western Borefield wells before 1960 were similar to concentrations observed in the deep recharge area at Te Mihi (**Figure 3(c)**).

Up to 1998 the reservoir chloride for all the Western Borefield wells declined steadily from the original value of ~ 1600 to about 1350 mg/L. This trend is evident in the representative wells plotted in **Figure 3(c).** After 1998 the declining Cl trend was arrested. In WK27, 30 and 67 the trend leveled off at about 1400 mg/L. WK55 appears to be more sensitive and showed a small increase in Cl from 1998-2005, and has since reverted to a declining trend.

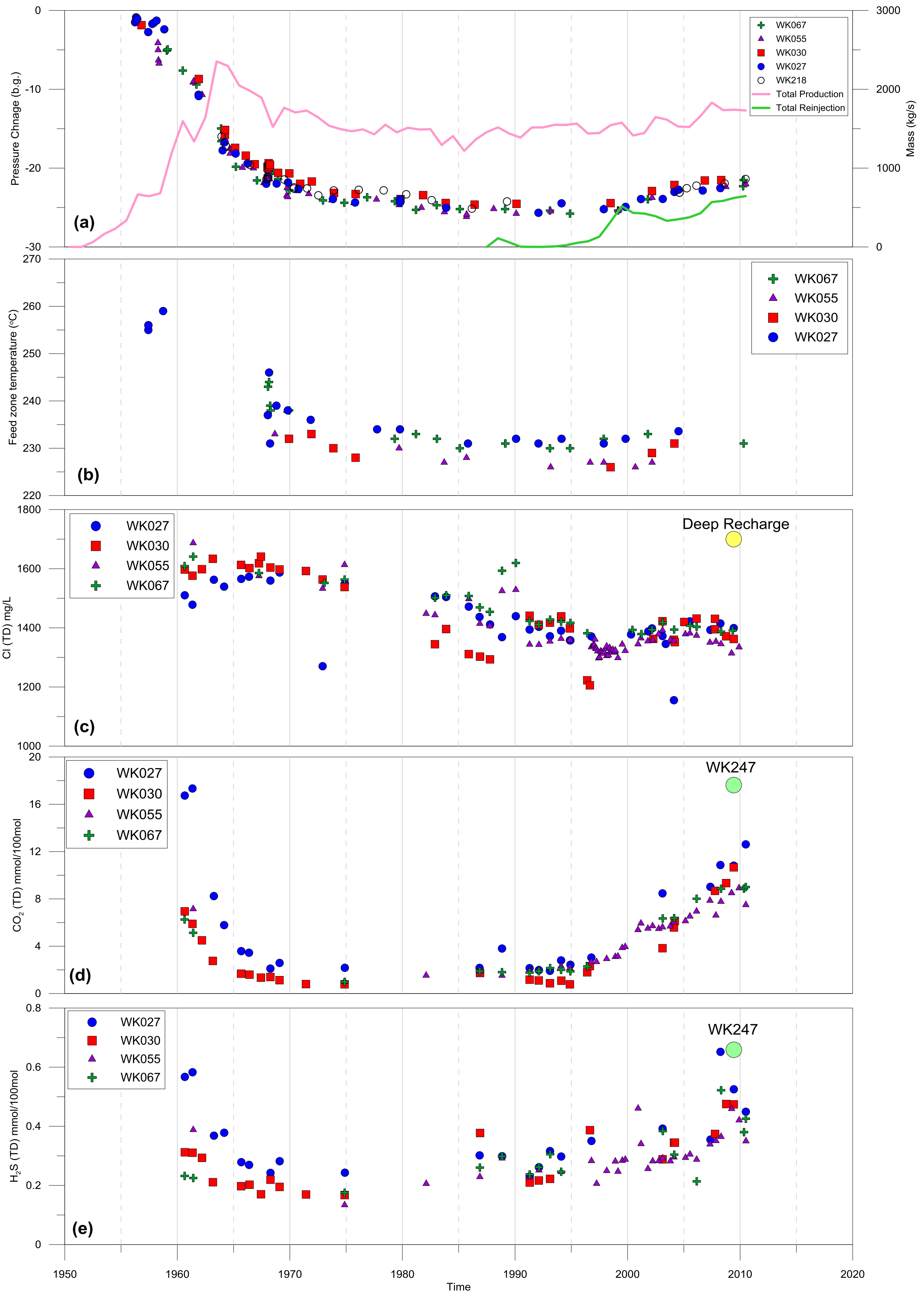

Figure 3 (a): Wairakei pressures over time for key Western Borefield wells. WK218, a pressure monitor well & total yearly field production & reinjection is also illustrated; (b): Liquid feed zone temperatures over time; (c): Reservoir chloride concentrations over time compared to 'deep recharge'. Deep recharge taken from Brown et al, 1988; (d): Carbon dioxide concentrations in total discharge over time also; (e): Hydrogen sulphide concentrations in total discharge over time. WK247 carbon dioxide and hydrogen sulphide values are used for comparison in (d) and (e) as this well is Wairakei's deepest production well.

3.4 Gas Composition

Carbon dioxide concentrations of ~6 mmol/100mol with some values up to 23 mmol/100mol were typical for Western Borefeld production wells prior to 1960 (Mahon 1969, (**Figure 3(a)**). After 1960 the CO_2 concentration rapidly declined from these initial values and from 1970-1995 was stable at about 2 mmol/100mol. Similarly the H_2S concentrations were typically 0.2-0.3 mmol/100mol from 1970-1995 (**Figure 3(d)** and **Figure 3(e)**).

From 1998, CO_2 concentrations demonstrate a strong increasing trend, and by 2010 were typically around 10 mmol/100mol, five times the pre-injection values. Hydrogen sulphide concentrations showed a small but consistent change, increasing from about 0.3 to 0.4 mmol/100mol.

Some cases, as in **Figure 3(d),** show CO_2 concentrations rise beyond initially measured levels (WK030, WK055 and WK067) but do not reach levels measured closer towards the deep recharge. WK247 is used for comparison in **Figure 3 (d) and (e)** as it is located near the known deep recharge and is the deepest production well.

4 POST REINJECTION RESERVOIR BEHAVIOUR

The production wells in the Western Borefield appear to be influenced by a combination of direct and indirect effects of reinjection, plus other unrelated factors that occurred about the same time as reinjection commenced. These influences are discussed below.

4.1 Reinjection Returns at Wairakei

Over 40 tracer tests have been performed at Wairakei (Bixley et al, 2009). The early tracer tests were performed to assist in improving the understanding the reservoir hydrology before committing to large scale reinjection. Since reinjection started at Otupu, five tracer tests have been performed. Three of these tests used ^{131}I, with no sign of returns. Based on the results of later tests this was most likely due to the relatively short half-life of 8 days for ^{131}I and long return times. One of these tests was repeated using naphthalene disulfonic acid (NDSA) and ^{125}I (half-life 60 days) tracers. For both tracers very low level returns were detected in the Western Borefield after 200 days.

The chloride content of the reinjection brine at Otupu was about 1800 mg/L compared with the pre-injection fluid produced in the Western Borefield of about 1350 mg/L. As discussed above, the production well chemistry indicates that chloride concentration increased by up to 50 mg/L after reinjection started. If this change was solely due to reinjection, returns of about 12% reinjected fluid to the production wells would be required.

However, indications of such strong reinjection returns are not supported by the low levels of tracer returns, and increasing trends in both production temperature and CO_2 content.

4.2 Secondary Effects of Reservoir Pressure Changes

The increase in CO_2, by more than five times, could be explained by assuming that the general increase in reservoir pressures from 1998-2010, caused by reinjection, has suppressed boiling in the ascending deep recharge in the Te Mihi area, and that this less-boiled deep recharge fluid is supplying the Western Borefield. Such a mechanism could explain the CO_2 increase, and the small increases in both feedzone temperature and chloride content, although both of the latter factors are also affected by dilution from cooler fluids (Glover & Mroczek, 2009).

Such a mechanism would also be expected to impact on the shallow steam zone, at least in the areas directly overlying the upflow area, by reducing the upflow of boiling fluid and non-condensable gases. No obvious changes in the pressure and gas trends in the steam zone wells have been observed, although this is complicated by variations in the steam extraction rate over time.

4.3 Factors Unrelated to Reinjection

About the same time as reinjection started, some of the natural features and shallow groundwater levels in a small area toward the northwestern edge of the Western Borefield ("Alum Lakes") developed new trends. Taken together, these indicated that the shallow groundwaters in this area had developed a new connection to the deeper resource, and a significant downflow of cool shallow groundwater had developed (Bromley, 2009).

This "new" water impacted on the production well chemistry, increasing the sulphate and calcium concentration in some areas (Glover & Mroczek, 2009).

The combination of higher CO_2 and increasing calcium after 2000 appears to be the cause of the sudden development of calcite scale in some Western Borefield production wells.

5 DISCUSSION

It is clear that there is a correlation between a decrease in reservoir pressure and temperature with CO_2 and H_2S reservoir concentrations during the early development of the field (**Figure 3(a)**, **Figure 3(b)**, **Figure 3(d)**, **Figure 3(e)**). It also seems apparent that there is a correlation, again after 1998, when reinjection began and the reservoir pressure increased by 4 bar with an increase in gas content. As physical returns of reinjection fluid can only account for some of the observed changes an alternative explanation is proposed.

Boiling frequently occurs within geothermal systems. Fluid boils as a result of a change of pressure and temperature. Within the Wairakei field several 'layers' of two phase fluid as well as steam exist. This is a result of upflowing fluid boiling and creating a steam cap in the shallower section of the reservoir. As pressures increase in the deeper liquid part of the reservoir, the boiling point moves closer to the surface and boiling is suppressed (**Figure 4**). Thus during the period when pressure is increasing less gas is boiled from the deeper reservoir fluid and more gas remains in the fluid that travels from the upflow zone at Te Mihi, to the outflow zone at the Western Borefield (**Figure 4**). For example, a compound such as CO_2 is readily lost to the vapour phase when a pressure regime changes (Mahon, 1962). Thus in the Western Borefield wells, carbon dioxide trends have followed pressure trends reflecting the amount of boiling in the deep recharge over time. (**Figure 3(a)** and **Figure 3(b)**).

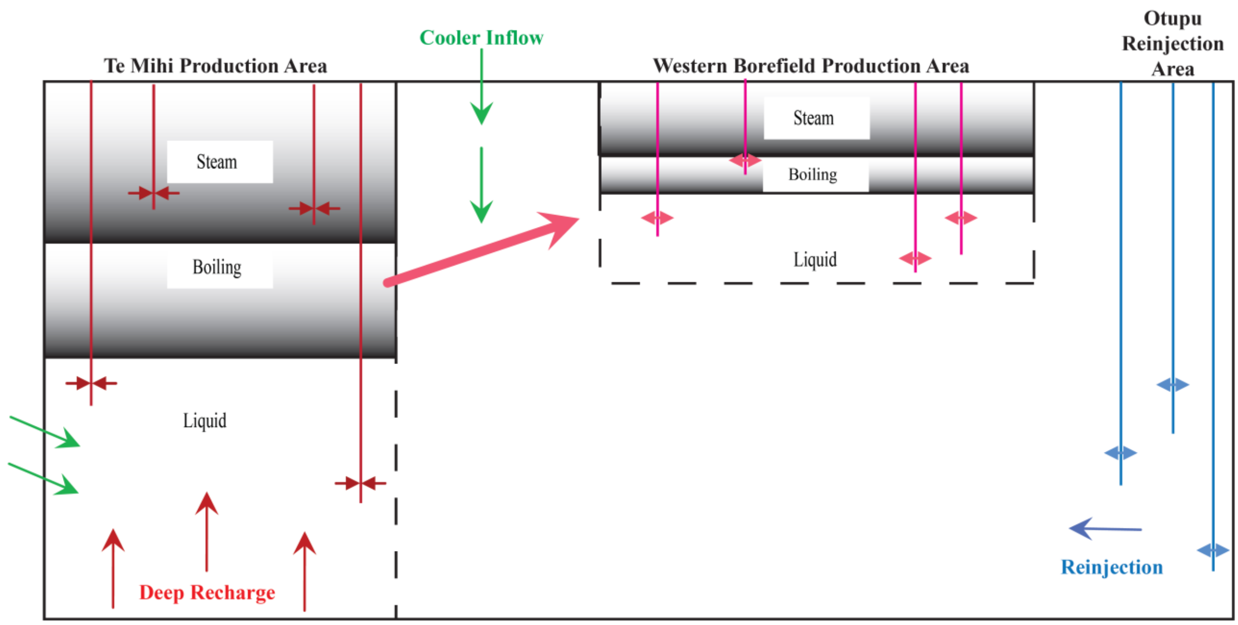

Figure 5: Schematic diagram of the multiple effects influencing the well output of Wairakei's Western Borefield wells once reinjection commenced (post 1998).

5 CONCLUSION

The experience at Wairakei has shown that large scale reinjection is not necessarily required to sustain the geothermal resource, and in fact, the pressure drawdown has resulted in significant increase in the deep hot recharge enhancing sustainability. However, managing the environmental effects of surface discharge means that reinjection is a vital part of managing the Wairakei geothermal field. Monitoring for reinjection returns is important to ensure any adverse effect are detected and managed in a sustainable way. In the case of the Wairakei Geothermal Field, indirect or secondary effects of reinjection are just as important to monitor and understand. As an example, boiling point migration due to increased pressure from reinjection has modified the behaviour of some production wells (such as gas output). Other unrelated phenomena, such as effects from cooler downflowing fluids, may complicate the effort to understand and characterize the impact of reinjection. Thus, although reinjection management is often focused on minimizing adverse effect from physical reinjection returns, it may be equally important to understand and manage secondary effects.

ACKNOWLEDGEMENTS

The authors wish to thank Contact Energy for permission to publish this paper and the associated data. Thank you also to those who reviewed this paper: Zim Aunzo, Warren Mannington and Christine Siega.

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