PROCEEDINGS, 50th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 10-12, 2025
SGP-TR-229

Sustaining Hot Spring Activity in the Vicinity of Geothermal Developments

Stuart F. Simmons, Mark L. Rockhold and Rebecca Kreuzer

EGI, University of Utah, Salt Lake City, UT and Pacific Northwest National Laboratory, Richland, WA

ssimmons@egi.utah.edu; mark.rockhold@pnnl.gov; rebecca.kreuzer@pnnl.gov

Keywords: Hot springs, geothermal production, monitoring, injection, New Zealand, USA.

ABSTRACT

Hot springs represent a continuum of surface features associated with hydrothermal activity and high-medium enthalpy geothermal resources. In some fields, such surface expression has proven to be vulnerable to what appears to be irreversible change in the wake of geothermal development, particularly at early stages of fluid production. The record of activities in New Zealand and the western USA shows that near boiling springs and geysers, are particularly sensitive to pressure induced lowering of the water table, becoming inactive, and in some cases replaced by zones of steaming ground. The geological control on the flow and ascent of hot water is an important factor in governing the magnitude of induced effects. But permeability is a unique geological attribute, and no two hydrothermal systems are exactly alike. For this reason, there are also examples where hot spring activity is unaffected by and much less sensitive to geothermal production due to structural and stratigraphic compartmentalization. Such geological factors in combination with injection strategies minimize induced pressure change and provide insights of how surface thermal activity can be protected and monitored in the vicinity of geothermal production fields. Case studies of fields in New Zealand and the western USA will be covered to illustrate these points.

1. INTRODUCTION

Hot springs are the surface expression of subsurface hydrothermal activity associated with geothermal resources, and they have long been used at early stages of exploration to evaluate the underlying potential for geothermal development (Hochstein & Browne, 2000; Simmons, 2020). As they form near the water table, hot springs are subject to change and degradation due to geothermal production in response to depressurization and lowering of water levels (e.g., Sorey, 2000). Growing awareness and perception that such changes in surface features might be irreversible has relevance for permitting new geothermal production fields for electricity generation (e.g., Kruezer et al., 2024). However, this is not the only activity that can impact surface discharge of thermal fluids. The pressure regime of shallow hydrothermal aquifers may be affected by groundwater use for irrigation and agriculture, changes in seasonal rainfall, and competing interests in geothermal production used directly for heating or recreational purposes. Furthermore, hot springs evolve naturally due to cooling of the heat source and waning hydrothermal upflow, changes in the water table or underlying permeability structure, and volcanic eruption (e.g., Lloyd, 1959; Simmons et al., 1993; 2021).

This paper represents a progress report of a study on the effects of geothermal production on surface thermal activity with focus on occurrences in the North Island of New Zealand and the Basin and Range province, western USA (Figure 1), based on published papers and unpublished reports. In these areas, the terrain is relatively flat, and the geothermal water table or piezometric level is marked by hot springs that discharge chloride and bicarbonate-rich waters. Following a brief review of historical impacts on surface activity induced by geothermal production, the characteristics of three New Zealand fields where surface thermal activity has been sustained through monitoring and injection are covered. These are used to demonstrate the diverse nature of hydrological settings of hot spring activity, and to document the different circumstances and approaches to monitoring and injection that minimize impacts. The evidence suggests that hot springs are more resilient than what might be expected, especially if preproduction pressure regimes can be sustained.

2. PRODUCTION INDUCED EFFECTS FROM 1950 TO 1990

In the earliest developments of liquid-dominated geothermal reservoirs, the preservation of natural hot spring activity was neglected to meet power needs, whether it be for electricity generation or direct use heating. Such were the circumstances at Wairakei, New Zealand, where the loss of boiling hot springs and geysers in Geyser Valley was a direct effect of large-scale geothermal fluid production starting in 1958 (Bolton, 2009; Thain and Carey, 2009). In their natural state, these hot springs discharged near neutral pH chloride-rich waters that compositionally strongly resembled the deep upflow (Glover and Mroczek, 2009). The drop in chloride that accompanied decreasing flows was a clear sign of declining pressure and dropping water level induced by production (White and Hunt, 2005). Production without injection induced a 30 bar drop in reservoir pressure over a 10-year period that propagated laterally through the Waiora formation, a porous and permeable interval of horizontally bedded strata that is capped by poorly permeable lake sediments of the Huka Falls formation (e.g. Bixley et al., 2009). The effects of depressurization extended laterally covering an area >10 km^2, eventually affecting the flow of boiling hot water in the adjacent Tauhara field (Henley and Stewart, 1983). A separate but related effect of reservoir depressurization was the expansion of steaming ground in the Karapiti area (Allis, 1981), south of the Wairakei production field, which since the 1980s has turned into a tourist attraction. Other examples of production induced changes to surface activity occurred at Ohaaki, and Rotorua, in New Zealand, and Beowawe and Roosevelt Hot Springs, in Utah and Nevada, respectively, as described below.

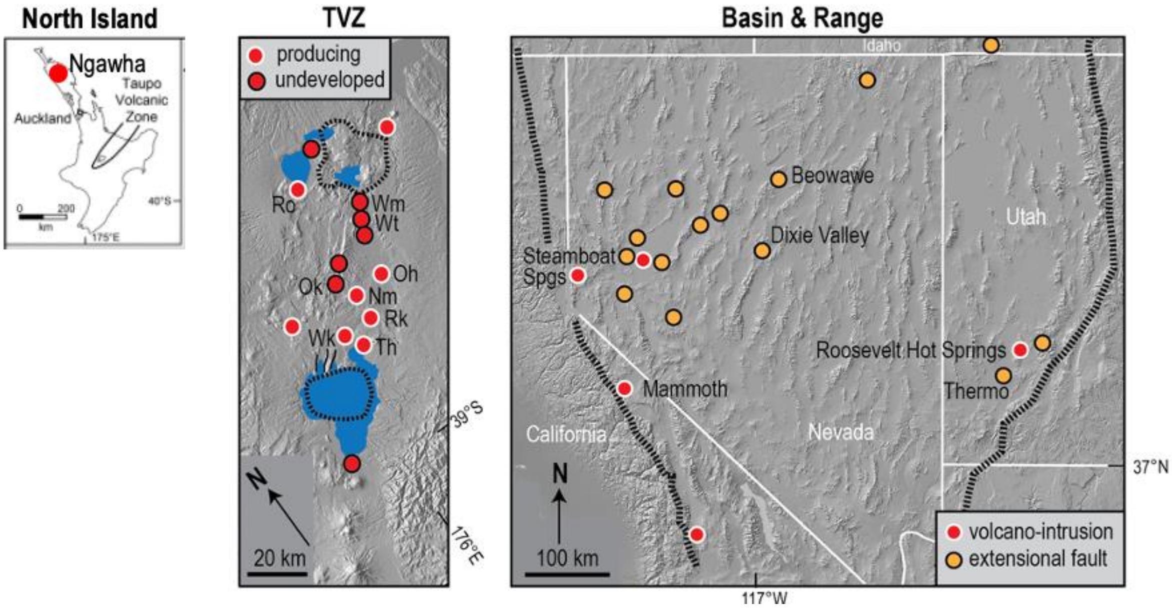

Figure 1. Maps showing locations of geothermal production fields in the North Island, New Zealand and the western USA Basin and Range referred to in the text. New Zealand map abbreviations: Ngā Tamariki=Nm; Ohaaki=Oh; Orakeikorako=Ok Rotokawa=Rk; Rotorua=Ro; Tauhara=Th; Taupo Volcanic Zone=TVZ; Waimangu=Wm; Waiotapu=Wt; Wairakei=Wk.

Surface activity in the Ohaaki field is dominated by the Ohaki ngāwhā (formerly known as the Ohaki pool), which fills a large sinter lined basin (~400 m^2) that in its natural state discharged (up to 10 l/s) near boiling chloride-bicarbonate water (Glover et al., 1996). From drilling and production testing in the 1960s-1970s, the water level was shown to be affected by production and fault-controlled fluid flow (Grindley and Browne, 1968). The power station was not commissioned until 1988, but unlike Wairakei, reinjection was used to manage disposal of separated wastewater from the start. The ngāwhā water level was maintained through the mid 1990s when cracking of the base possibly induced by subsidence, and/or reported seismicity, caused the pool to completely drain away (Glover et al., 2000). Subsequent remediation involved sealing the floor of the basin and plumbing a subsurface pipeline to supply hot separated production water.

The city of Rotorua is internationally renowned for being built on a high-temperature hydrothermal system, with over 1500 natural thermal features, including mud pools, boiling hot springs and geysers (Allis and Lumb, 1992; Bay of Plenty Regional Council, 2024). Geothermal energy has been directly used for bathing, cooking, heating and well-being for centuries, first by Māori who attribute deep cultural value to surface thermal activity, and much later by residents who drilled wells for domestic-commercial heating. In the late 1970s and early 1980s, borehole mass withdrawal exceeded 30,000 tonnes/day with minimal reinjection, and by 1987, perceived declines in hot spring and geyser activity led to the closure of all bores within a 1.5 km radius of Pohutu geyser in the southern part of the city (Allis and Lumb, 1992; Bradford, 1992). The immediate effects proved to be impactful, leading to recovery of shallow aquifer pressure and of hot springs and geysers (Bradford, 1992; Cody and Lumb, 1992). Although production was small compared to other developments in New Zealand, the pressure declines of <1 bar, affected water levels by a few meters, leading to inference that rainfall and drought could be relevant factors that affect hot spring activity too (Bradford, 1992). Through the ensuing decades, hot spring activity rejuvenated across the field, including in a few long dormant vents (Scott et al., 2005). Overall, the long-term monitoring of shallow wells, indicator springs, and discharge compositions, supported by numerical modeling has been an effective in understanding cause and effect processes (Scott et al., 2016). Such data and analysis underpin the long adopted integrated approach of sustainable resource management enshrined in local government policy (Bay of Plenty Regional Council, 2024).

At Roosevelt Hot Springs, high temperature hydrothermal activity is entirely contained in fractured crystalline basement rock made of granitoids (Tertiary) and gneiss (Precambrian), and natural surface features were restricted to a small area of sub-boiling hot spring discharge and seepage in the northwest part of the field. When geothermal production started in 1984 with commissioning of the Blundell power plant (26 MWe), these features may have already been in decline (Capuano and Cole, 1982). Despite being accompanied by reinjection, the reservoir pressure dropped 30 bars over the first four years of geothermal production, causing a lowering of the water table and the formation of an overlying steam zone (Allis and Larsen, 2012). Surface hot water discharge ceased, and in its place, a broader zone of steaming ground developed, resembling production induced effects at Wairakei (Simmons et al., 2021). The Opal Mound, a 1600–1900-year-old silica sinter deposit occurring in the southwest part of the field at the southern terminus of the Opal Mound fault, provides separate evidence of decline in boiling hot spring discharge that occurred naturally. This is despite overlying a modern zone of boiling upflow, indicating that fault-controlled fluid flow and hot spring discharge have occurred sporadically over the lifespan of the hydrothermal system.

At Beowawe in 1959, long before power generation was commissioned, the active sinter terrace along the Malpais fault was drilled, and subsequent uncontrolled well flows related to vandalism caused pressure declines and termination of geysering discharge (Smith, 1983; White, 1992). Although not widely appreciated at the time, Beowawe had the second largest concentration of geysers in the USA after Yellowstone, and in its undisturbed state, comprised at least 10 individual vents with fountaining discharge erupting up to a height of 8 m (White, 1992). All natural discharge ceased by 1960 due to depressurization of the structurally controlled fluid flow, while artificial geysering discharged from uncapped wells into the early 1980s (Smith, 1983, Garg et al., 2007). These changes predate the ultimate commissioning of the power station in 1985, and although reinjection was employed from the start, it was insufficient in resuscitating hot spring activity (Benoit and Stock, 1993).

The foregoing records illustrate that drop in aquifer pressure and lowering of water levels in response to geothermal production are key factors that induced decline of surface thermal activity. The experience at Rotorua furthermore provides evidence that hot spring activity can be restored if subsurface pressure recovers, which in that case was managed by reducing production in a localized sector of the field. A similar effect involving the restoration of surface thermal activity occurred naturally at Waimangu where pre-existing surface activity was drastically modified by shallow depressurization of hydrothermal aquifers in the wake of the 1886 volcanic eruption of Mt Tarawera (Simmons and O'Sullivan, 2010).

3. GEOTHERMAL PRODUCTION AND SUSTAINED SURFACE THERMAL ACTIVITY IN NEW ZEALAND

In 1991, New Zealand passed the Resource Management Act which established the modern legal framework by which geothermal resources and the host environments are managed sustainably, including those with natural surface thermal activity (Thain, 1992; Doorman and McLeod, 2018). In the years that followed, the legislation has been reformed and additional changes are expected (McLean et al., 2023), but it is in this context that geothermal fields have been regulated over the last 30 years. The summaries of the developments at Ngawha, Ngā Tamariki and Rotokawa that follow provide examples of where natural surface thermal activity has been sustained. Their geological-hydrological characteristics and production-injector sectors are schematically portrayed in Figure 2.

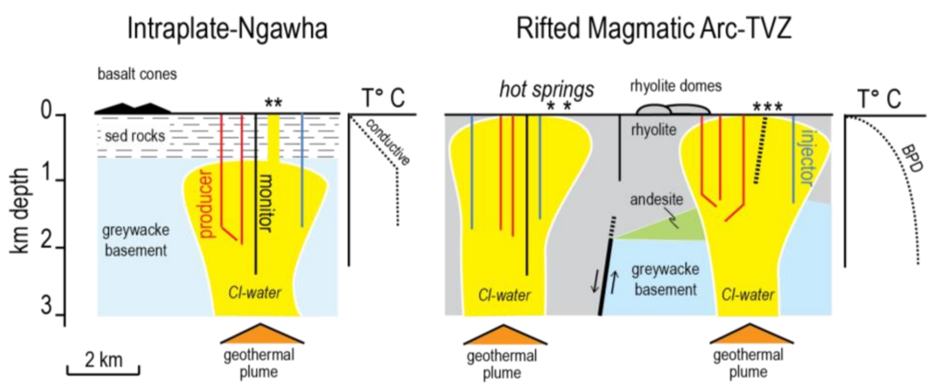

Figure 2. Schematic cross sections of geothermal resources in the North Island, New Zealand showing the differing positioning of production, injection and monitor wells with respect to the hydrothermal plumes that host reservoirs (yellow), hot springs (asterisk symbol), and geological context. Production wells are shown in red, injector wells are shown in blue, and monitor wells are shown in black. The temperature profiles represent conditions of the upflow zone; BPD = boiling point for depth.

3.1 Ngawha

The Ngawha geothermal area (~10-15 km^2) is located within the late Miocene–Holocene Kerikeri basaltic volcanic field, and the main geothermal surface features comprise neutral to acid thermal pools (30° to 60 °C), gas seeps, and cold gas bubbling lakes (Simmons et al., 2005). Thermal springs are aligned with a NE–SW trending fault (Skinner, 1981; Petty, 1985), and although their total discharge is low (1–2 l/s, total), it is accompanied by vigorous CO_2 gas flux (Sheppard and Johnston,1985; Scott and Glover, 2000; Glover and Scott, 2005). The geothermal reservoir is hosted by fractured metasedimentary rocks at 500 to 600 m beneath the surface. The overlying interval of Cretaceous–Tertiary sedimentary rocks is made of siltstones, mudstones, limestones and shales, interleaved with zones of tectonic breccia (Skinner, 1981; Petty, 1985). The temperature profiles in wells indicate that this upper stratigraphy (down to ~500 m depth) is characterized by a conductive thermal gradient and sub-boiling conditions due to very low permeability. The deep reservoir water at Ngawha has a temperature of about 230 °C and contains 1–2 wt.% CO_2 (Sheppard and Giggenbach, 1985). This fluid is slightly over-pressured with respect to a hot hydrostatic boiling point for depth gradient, due to the confining nature of the shallow sedimentary strata and the relatively high concentration of aqueous CO_2 (Browne and Lawless, 2001).

Ngawha springs have been used for bathing for over a century. Geothermal exploration was initiated in the 1960s with deep drilling of a single well. A major drilling campaign followed in the period 1978-1984, in which an additional 13 wells were completed. Despite outlining a viable resource at ~220-230 °C, it was not until 1997 that the first stage of power generation was developed with commissioning of the OEC 1/2 binary units (10 MWe), using fluid from just two wells. In 2008, production expanded to 25 MWe with commissioning of OEC 3. By 2021, an additional 8 deep wells were completed, and the OEC 4 binary plant was commissioned, which extended total power generation to 57 MWe. With each of these expansions, the consented production grew from 10,000 tonne/day to 25,500 tonne/day to 51,200 tonne/day. The chemistry of produced fluid from spatially distributed wells was and has remained uniform, containing ~1250 ppm Cl and ~900 ppm B (Sheppard and Giggenbach, 1985; Scott and Glover, 2000; Glover and Scott, 2005; Robinson, 2024).

The authorized consent for geothermal production has from the start required stringent monitoring which is used to identify and mitigate adverse effects on the physical and chemical character of the hot springs. From previous time-series measurements and fluid analyses dating back to before 1980, there was clear indication of spatial and temporal variability in spring discharge compositions (Sheppard and Johnston, 1985). For example, in the period 1980 to 1983, Tiger bath displayed wide fluctuation in Cl concentration (<50 to >800 ppm) with moderate change in temperature (30 to 50 °C), Universal bath displayed moderate fluctuation in Cl (350 to 450 ppm) and temperature (37 to 47 °C), as did Jubilee bath (700 to 1300 ppm Cl; 41 to 51 °C). For all three springs, Cl/B values were nearly uniform, with no variability, indicating a varying supply and discharge of deep fluid composition water from the underlying geothermal reservoir. A decade later, the baseline preproduction environmental monitoring (1996-1997) showed a similar degree of variability. Such secular variation is attributed to hydrologic interaction between the upflow of deep reservoir fluid, shallow groundwaters enriched in bicarbonate, and rainfall (Sheppard and Johnston, 1985; Scott and Glover, 2000; Glover and Scott, 2005). Since the start of power generation, these three features have been monitored by monthly to quarterly temperature measurement and sampling-analysis of fluid chemistry (Scott and Glover, 2000; Glover and Scott, 2005); additional springs have been monitored as required. From the data collected, Jubilee bath has consistently discharged a high proportion of deep reservoir fluid, with minimal change in composition and temperature, and with no evidence of production induced effects based on time-series trends in Figure 3. In support to the spring monitoring program, Ng13 (2175 m) is used to continuously monitor reservoir pressure, and the data show variation of less than ± 1 bar since 2001. Overall, the monitoring data reported semi-annually indicate that while geothermal production in the period 1997 to 2024 has increased, there has been no measurable impact on surface thermal activity (Robinson, 2024; Riddle, 2024).

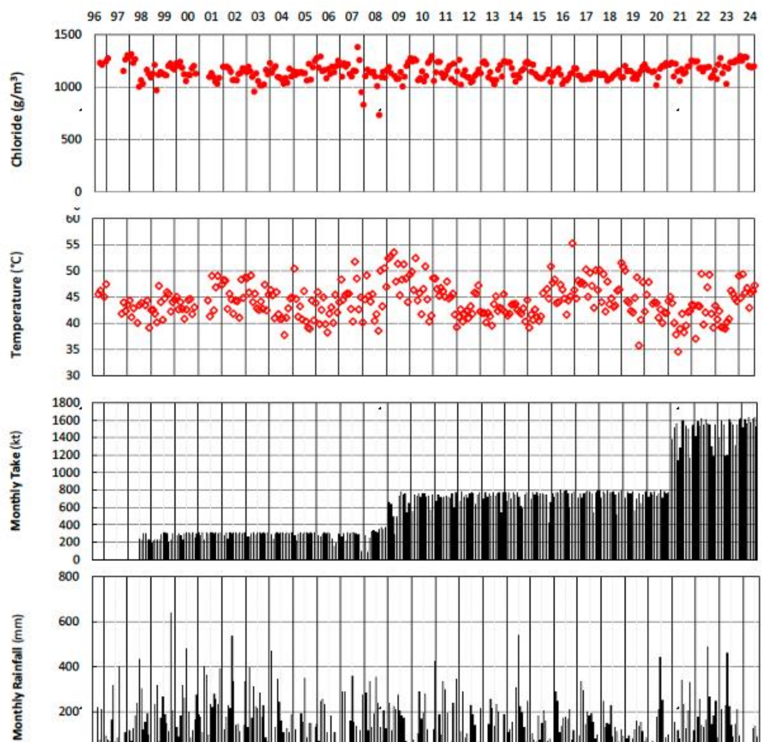

Figure 3. Jubilee bath time series graphs showing the long-term trends in chloride and temperature in relation to geothermal fluid production and rainfall (Riddle, 2024).

3.2 Ngā Tamariki

The Ngā Tamariki geothermal field (~10 km^2) occurs in the central Taupo Volcanic Zone, north of the Rotokawa but south of the undeveloped and protected Orakeikorako field (Figure 1). Surface thermal activity is restricted to the northern part of the field, where approximately ten sinter-travertine depositing springs discharge bicarbonate-chloride water (70-94 °C) along Orakonui stream and the banks the Waikato River (Cody et al., 2021). The field was initially explored with the completion of deep wells in the 1980s that proved a hot resource >250 °C between 600 and 2000 m depth. Twenty years later and with the benefit of recent geophysical surveys, additional drilling proved the commercial viability of the field, and four binary units totaling 86 MWe were commissioned in 2013. A small-scale hydrothermal eruption occurred in 2005 (Simpson et al., 2014), but this was a natural occurrence predating geothermal production. The geothermal reservoir is hosted within horizontally bedded volcanic strata having a reservoir temperature of 260-285 °C, and the upflow zone underlies an isolated thermal aquifer at 300-600 m depth, and a shallower cold-water aquifer (Boseley et al., 2010; Chambefort et al., 2016). The chemistry of waters from surface features reflect intermixing between the deep reservoir fluid and water from the intermediate thermal aquifer. Production is limited to 60,000 tonnes/day that comes from four centrally located wells, which are bounded by three edge-field injectors to the north and two edge-field injectors to the south; reinjection is placed at reservoir depth.

Consent for production explicitly requires avoidance of pressure drawdown, adverse effects on surface thermal activity at Orakeikorako (Lloyd, 1972), and contamination of freshwater aquifers (Mercury, 2018). To achieve this the utilization of binary plant technology means that close to 100% of the produced fluid is reinjected, maintaining reservoir pressure. Additionally, twenty-nine spatially distributed wells occupying infield, edge-field and outfield locations and spanning a depth range of 10 to 520 m are used to monitor the two upper aquifers for temperature, pressure and chemistry from continuously to monthly to twice-yearly (Mering et al., 2024).

Over the last ten years, deep reservoir monitoring shows variation of less than ±1 bar, and surface thermal activity continues within a range that relates to natural variation (Mercury, 2024; Mering et al., 2024). This includes Orakeikorako where additionally there is no evidence of production-induced effects on hot spring activity or on the subsurface pressure regime based on the monitoring of spatially distributed wells.

3.3 Rotokawa

Rotokawa (~28 km^2) is one of the hottest geothermal resources in the central Taupo Volcanic Zone. It is bisected by the Waikato River, and geothermal development is mostly limited to the southern part of the field. Surface thermal activity is also primarily restricted to the southern part of the field, where springs discharge mainly acid-sulfate-chloride waters ranging from 70-95 °C in the vicinity of Lake Rotokawa and Parariki stream (Cody et al., 2021). Additional natural subaqueous discharge is associated with springs and seeps in the Waikato River channel. Geologically relevant is the alignment of at least eight separate hydrothermal eruption vents (Collar and Browne, 1985, Browne and Lawless, 2001; Rowland and Simmons, 2012), and these delineate the NE trending Central Field fault that acts as a flow barrier between the production sector to the west and the injection sector to the east (McNamara et al., 2016).

The first phase of geothermal exploration was carried out in the 1960s-1970s, during which three wells were completed. In the 1980s, five additional wells were drilled proving the existence of a resource up to ~330 °C. In this same time-period, the potential for mining sulfur was being investigated involving shallow drilling in the vicinity of Lake Rotokawa which caused considerable surface disturbance. In the mid 1990s, further geothermal investigations included completion of three additional wells that led to the commissioning in 1997 of the Rotokawa power station (24 MWe), which comprised a steam turbine and three binary units. With a change in management, the plant capacity was expanded in 2002 to 34 MWe, and in 2010, Nga Awa Purua, a 140 MWe triple flash plant, was commissioned. Modern production is limited to 75,500 tonnes/day coming from 12 deep wells, located in the southwest part of the field, along a NE-SW trending corridor. Three infield injection wells are used to dispose of thermal water from the Rotokawa power station, whereas the much larger load of separated water and condensate from Nga Awa Purua is mostly injected into three deep wells on eastern side the field.

The geothermal reservoir is hosted within horizontally bedded volcanic strata that is transected by several NE-SW trending normal faults that impose strong control on fluid flow. The large step change in production with the start of Nga Awa Purua induced a localized pressure drop of up to 40 bar (Quinao et al., 2013; Mercury, 2022), and yet two km to the south, the thermal features in the vicinity of Lake Rotokawa remained unchanged (Mercury, 2023). There are no monitoring wells in this part of the field, but a large number of thermal features are monitored annually, involving measurements or observations of temperature, chemistry and flow. While flow rates and temperature can show strong fluctuation, chloride remains relatively uniform, and the mean values since 2000 show minimal change. Unlike Wairakei and Ohaaki, these records indicate that natural surface thermal activity is sustainable and protected by fault-related barriers despite large nearby changes in the pressure regime induced by geothermal production.

4. SYNTHESIS

Based on studies and reports in the western USA, primarily Mammoth-Long Valley, Steamboat Springs, and Beowawe (Figure 1), Sorey (2000) concluded that "changes in surficial thermal features and land elevations accompanying geothermal development should be viewed as the rule, rather than the exception". Based on the experience up to the time of that publication, such a judgment was substantiated by data from both the USA and New Zealand. However, as summarized herein, there are several subsequent geothermal developments in New Zealand that show the opposite outcome in which natural surface thermal activity is sustained. These have been achieved in fields that involve redistribution of geothermal fluid mass via production and that in at least one case (Rotokawa) induced a significant pressure drop. We expect there are other examples too based on field observations (e.g., Thermo Utah) but for which documentation and monitoring data are unpublished or unavailable.

Three key factors contribute to mitigating adverse effects on surface features as presented in the case studies covered above. Most important is reinjection of as close to as possible of 100% of the produced fluid. This has proven to be effective at maintaining subsurface pressure regimes at Ngawha and Ngā Tamariki, where surface thermal activity shows no signs of production-induced change in flow, temperature or composition. Locations for reinjection are also relevant, since reinjected water is typically cooler than produced water, so time and distance are needed to reheat reinjected water used for pressure support. For Ngā Tamariki, the placement of injection (and monitoring) wells between the production sector and surface thermal activity appears to have been particularly successful (Mering et al., 2024).

Another factor deals with heterogeneity in porosity and permeability associated with the package of rocks hosting the reservoir. The evidence suggests that geological barriers and baffles in the form of aquicludes and fault structures can protect surface features from adverse effects. Unfortunately, they can be difficult to identify until mature stages of exploration, and confirmation might be only attained through production-injection testing sometimes lasting several years and in association with phased developments.

The final factor is environmental monitoring of surface features and subsurface pressure regimes. Characterization of preproduction fluctuations in flow, temperature and chemistry of hot spring waters provides baseline data for understanding controls on the shallow hydrology including ones related to natural and anthropogenic effects. Where feasible, the early incorporation of such data into numerical models provides a useful tool in forecasting and managing potential effects. From these results, index features can be selected and time intervals of sampling and measurement can be determined. By the time resource development commences (i.e., post-exploration and pre-production) infrastructure to monitor pressure regimes is phased in with dedicated wells designed to characterize temporal variations at shallow (<100 m), intermediate (~100-500 m), and deep (~800-1000 m) levels below the piezometric surface or water table. Their locations and spacing are tailored to local monitoring needs and as subsurface understanding improves with the aim of mitigating production-induced effects.

5. ACKNOWLEDGEMENTS

Funding for this project is provided by the Department of Energy's Geothermal Technologies Office (DOE-GTO). Permission to publish the time series data for Jubilee bath was obtained from Ngawha Generation Ltd and NZ Environmental Ltd. Access to annual reports and the system management plans at Ngā Tamariki (Mercury NZ Ltd.), Rotokawa (Mercury NZ Ltd.), and Ohaaki (Contact Energy Ltd.) was facilitated by the Waikato Regional Council, and information about Rotorua was provided by the Bay of Plenty Regional Council. Thanks are extended to Ray Robinson, Cale Riddle, Nicola Bull, Jim McLeod, Mariana Zuquim, Farrell Siega and Bridget Ayling for comments and assistance in accessing information.

REFERENCES

Allis, R.G.: Changes in heat flow associated with exploitation of Wairakei geothermal field, New Zealand, New Zealand Journal of Geology and Geophysics, 24, (1981), 1-19.

Allis, R.G., and Lumb, J. T.: The Rotorua geothermal field, New Zealand: its physical setting, hydrology, and response to exploitation, Geothermics, 21, (1992), 7-24.

Allis, R.G., and Larsen, G.: Roosevelt Hot Springs Geothermal field, Utah—Reservoir response after more than 25 years of power production, Proceedings, 37th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, (2012).

Bay of Plenty Regional Council: *Ngā Wai Ariki o Rotorua He Mahere Whakahaere Pūnaha* Rotorua Geothermal System Management Plan, Bay of Plenty Regional Council, (2024), 52 p.

Benoit, D. and Stock, D.: A case history of injection at Beowawe, Nevada, Geothermal Reservoir, Geothermal Resource Council Transactions, 17, 1993, 473-480.

Bixley, P.F., Clotworthy, A.W., and Mannington, W.I.: Evolution of the Wairakei geothermal reservoir during 50 years of production, Geothermics, 38, 2009, 145-154.

Bolton, R.S.: The early history of Wairakei (with brief notes on some unforeseen outcomes), Geothermics, 38, 2009, 11-29.

Boseley, C., Cumming, W., Urzúa-Monsalve, L., Powell, T., and Grant, M.A.: A resource conceptual model for the Ngatamariki Geothermal Field based on recent exploration well drilling and 3D MT resistivity imaging, Proceedings of the World Geothermal Congress, Bali, Indonesia (2010).

Bradford, E.: Pressure changes in Rotorua geothermal aquifers, 1982-90, Geothermics, 21, (1992), 231-248.

Browne, P.R.L., and Lawless, J.V.: Characteristics of hydrothermal eruptions, with examples from New Zealand and elsewhere, Earth-Science Reviews, 52, (2001), 299-331.

Capuano, R.M., and Cole, D.R.: Fluid-mineral equilibria in a hydrothermal system, Geochimica et Cosmochimica Acta, 46, (1982), 1353-1364.

Chambefort, I., Buscarlet, E., Wallis, I.C., Sewell, S. and Wilmarth, M.: Ngatamariki geothermal field, New Zealand: geology, geophysics, chemistry and conceptual model, Geothermics, 59, (2016), 266-280.

Cody, A. D. and Lumb, J. T.: Changes in thermal activity in the Rotorua geothermal field, Geothermics, 21, (1992), 215-230.

Cody, A. D., Keam, R. F., Lebe, J., Lynne, B., and Luketina, K.: Sinter-forming springs and geysers of the Waikato Region, unpublished Waikato Regional Council report, (2021), 98 p.

Collar, R.J., and Browne, P.R.L.: Hydrothermal eruptions at the Rotokawa geothermal field, Taupo Volcanic Zone, New Zealand, Proceedings of the 7th New Zealand Geothermal Workshop, University of Auckland, Auckland, (1985), 171−175.

Doorman, P., and McLeod, J.: The changing face of geothermal system management plans in New Zealand, Proceedings of the 22nd New Zealand Geothermal Workshop, University of Auckland, Auckland (2018), 7 p.

Garg, S.K., Pritchett, J.W., Wannamaker, P. E., and Combs, J.: Characterization of geothermal reservoirs with electrical surveys: Beowawe geothermal field, Geothermics, 36, (2007), 487-517.

Glover, R.B., Hunt, T.M. and Severne, C.M.: Ohaaki ngawha, Ohaaki pool, Proceedings of the 18th New Zealand Geothermal Workshop, University of Auckland, Auckland, (1996), 77-84.

Glover, R.B., Hunt, T.M. and Severne, C.M.: Impacts of development on a natural thermal feature and their mitigation—Ohaaki Pool, New Zealand, Geothermics, 29, 2000, 509-523.

Glover, R.B., and Scott, T.M.: Geochemical monitoring before and during six years of power generation at Ngawha, New Zealand, Proceedings World Geothermal Congress, Ankara, Turkey, (2005), 6 p.

Glover, R.B. and Mroczek, E.K.: Chemical changes in natural features and well discharges in response to production at Wairakei, New Zealand, Geothermics, 38, 2009, 117-133.

Grindley, G.W. and Browne, P.R.L.: Subsurface geology of the Broadlands geothermal field, New Zealand Geological Survey Report 34, (1968), 41 p.

Henley, R.W. and Stewart, M.K.: Chemical and isotopic changes in the hydrology of the Tauhara geothermal field due to exploitation at Wairakei, Geothermics, 14, (1983), 285-314.

Hochstein, M.P. and Browne, P.R.L.: Surface manifestations of geothermal systems with volcanic heat sources, Encyclopedia of Volcanoes, Academic Press, (2000), 835-855.

Kreuzer, R., Rockhold, M., Diraddo, S., Duberstein, C., He, B., Steeves, T., and Simmons, S. Hot Springs and Geysers: Exploring Historical and Modern Impacts of Geothermal Energy Production on Associated Natural Surface Systems and Standardizing Management Practices. Geothermal Rising Conference (GRC) Transactions, (2024), 13 p.

Lloyd, E.F.: The hot springs and hydrothermal eruptions at Waiotapu, New Zealand Journal of Geology and Geophysics, 2, (1959), 141–176.

Lloyd, E.F.: Geology and hot springs of Orakeikorako, New Zealand Geological Survey Bulletin 85, (1972), 164 p.

McLean, K., Montague, T., Alcaraz, S., Daysh, S., Doorman, P., Luketina, K., Tsui, K., White, B., and Saddiq, Z.J.: 2020-2023 New Zealand country update, Proceedings World Geothermal Congress, Bejing, China, (2023), 18 p.

McNamara, D.D., Sewell, S., Buscarlet, E., and Wallis, I.,: A review of the Rotokawa geothermal field, New Zealand, Geothermics, 59, (2016), 281-293.

Mercury NZ Limited.: Ngā Tamariki System Management Plan, unpublished report Mercury NZ Limited for the Waikato Regional Council, (2018), 62 p.

Mercury NZ Limited.: Rotokawa System Management Plan, unpublished report Mercury NZ Limited for the Waikato Regional Council, (2022), 101 p.

Mercury NZ Limited.: Rotokawa Annual Report 2023, unpublished report Mercury NZ Limited for the Waikato Regional Council, (2023), 93 p.

Mercury NZ Limited.: Ngā Tamariki Annual Report, unpublished report Mercury NZ Limited for the Waikato Regional Council, (2024), 82 p.

Mering, J., Atayde, R., Utami, A., Estrella, C.M., and Fischer, C.: The role of groundwater monitoring in the sustainable management and operation of the Ngā Tamariki geothermal field, Proceedings of the 46th New Zealand Geothermal Workshop, University of Auckland, Auckland, (2024), 9 p.

Quinao, J., Sirad-Azwar, L., Clearwater, J., Hoepfinger, V., Le Brun, M., and Bardsley, C.: Analyses and modelling of the reservoir pressure changes to interpret the Rotokawa geothermal field response to the Nga Awa Purua power station operation, Proceedings, 38th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, (2013), 10 p.

Riddle, C.: Interim environmental monitoring report 2024, unpublished report by NZ Environmental Management for Ngawha Generation Limited and the Northland Regional Council, (2024), 37 p.

Petty, D.R.: A geological reappraisal of the Ngawha geothermal field, Department Scientific Industrial Research Geothermal Report 8, (1985), 17–32.

Robinson, R.: Production and re-injection well status, unpublished report Ngawha Generation Limited for the Northland Regional Council, (2024), 33 p.

Rowland, J. and Simmons, S. F.: Hydrologic, magmatic, and tectonic controls on hydrothermal flow, Taupo Volcanic Zone, New Zealand: Implications for the formation of epithermal vein deposits, Economic Geology, 107, (2012), 427-457.

Scott, B.J., Gordon, D.A. and Cody, A.D.: Recovery of Rotorua geothermal field, New Zealand: Progress, issues and consequences, Geothermics, 34, (2005), 161-185.

Scott, B.J., Mroczek, E.K., Burnell, J.G., Zarrouk, S.J., Seward, A., Robson, B. and Graham, D.J.: The Rotorua geothermal field: An experiment in environmental management, review of data sets, Geothermics, 59, (2016), 294-310.

Scott, T.M., and Glover, R.B.: Monitoring at Ngawha Springs before and after commissioning of the power station, Proceedings of the 22nd New Zealand Geothermal Workshop, University of Auckland, Auckland (2000), 197–202.

Sheppard, D.S., and Giggenbach, W.F.: Ngawha well fluid compositions, Department Scientific Industrial Research Geothermal Report 8, (1985), 103– 119.

Sheppard, D.S., and Johnston, J.R.: Monitoring of the natural thermal features at Ngawha springs, Department Scientific Industrial Research Geothermal Report 8, (1985), 121-144.

Simmons, S.F.: Geothermal Resources, Encyclopedia of Geology, 2nd Edition, Elsevier, 5, (2000), 708-722.

Simmons, S. F., Keywood, M., Scott, B.J. and Keam, R.F.: Irreversible change of the Rotomahana-Waimangu hydrothermal system (New Zealand) as a consequence of a volcanic eruption, Geology, 21, (1993), 643-646.

Simmons, S.F.: Harris, S.P., and Cassidy, J.: Lake-filled depressions resulting from cold gas discharge in the Ngawha geothermal field, New Zealand, Journal of Volcanology and Geothermal Research, (2005), 329-341.

Simmons, S. F., Allis, R.G., Kirby, S.M., Moore, J.N., and Fischer, T.P.: Interpretation of hydrothermal conditions, production- injection induced effects, and evidence for enhanced geothermal system type heat exchange in response to >30 years of production at Roosevelt Hot Springs, Utah, USA, Geosphere, 17, (2021), 30 p.

Simmons, S. F. and O'Sullivan, M.: Numerical model of the changes in geothermal activity in the Rotomahana-Waimangu system due to the 1886 eruption of Mt Tarawera, Proceedings World Geothermal Congress, Bali, Indonesia, (2010), 6 p.

Simpson, M.P., Rosenberg, M.D., Rae, A.J., Bignall, G., Mountain, B.W., Graham, D. and Chappell, D.: Insight into the 2005 hydrothermal eruption at South Orakonui, Ngatamariki geothermal field, New Zealand from calcite microthermometry, Proceedings of the New Zealand Geothermal Workshop 2014, University of Auckland, Auckland (2014), 6 p.

Skinner, D.N.B.: Geological setting and sub-surface geology of Ngawha, Department Scientific Industrial Research Geothermal Report 7, (1981),14– 35.

Smith, C.: Thermal hydrology and heat flow of Beowawe geothermal area, Nevada, Geophysics, 48, (1983), 618-626.

Sorey, M. L. Geothermal Development and Changes in Surficial Features: Examples from the Western United States, Proceedings World Geothermal Congress, Kyushu – Tohoku, Japan, (2000), 705-711.

Thain, I.A.: Impact of the Resource Management Act on future geothermal development in New Zealand, Geothermics, 21, (1992), 991-1000.

Thain, I.A.: Fifty years of geothermal power production at Wairakei, Geothermics, 38, 2009, 48-63.

White, D. E.: The Beowawe Geysers, Nevada, Before Geothermal Development, US Geological Survey Bulletin 1998, (1992), 25 p.

White, P.A. and Hunt, T.M.: Simple modelling of the effects of exploitation on hot springs, Geyser Valley, Wairakei, New Zealand, Geothermics, 34, (2005), 187-207.