MODELLING GEOTHERMAL SURFACE FEATURES IN THE ROTORUA GEOTHERMAL FIELD

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ABSTRACT

The Rotorua Geothermal Field is a shallow high enthalpy geothermal reservoir lying directly beneath the Rotorua city in New Zealand. It is renowned for an abundance of natural geothermal manifestations including the geysers and hot springs at Whakarewarewa. However surface geothermal activity waned in the 1970s and a decline in surface discharge of geothermal manifestations in response to excessive withdrawal of geothermal fluid was observed. A monitoring programme was instigated in 1982 followed by the introduction of a wellbore closure programme in 1986 which resulted in recovery of some surface features. As part of the Resource Management Act, forty-one of the most significant features have been monitored from May 2008. These records provide valuable insights on the state of the reservoir and health of the surface features in particular for field management purposes.

A full-scale three dimensional numerical model of the Rotorua geothermal system has been built to replicate the past and current behaviour of the geothermal field and surface features.

Correlation factors between the model outputs for the first ten layers (temperature and pressure) and temperatures recorded from May 2008 to September 2014 were calculated to determine a likely feed depth of the surface features at Rotorua. These were then used to implement wells on deliverability at the required depth. This is to explore various ways to represents surface features in a geothermal field. The aim is to complement and to help interpret the Rotorua monitoring programme data by providing a tool which can identify and replicate spatial and temporal trends of the surface features at Rotorua of natural and anthropogenic origins.

1. INTRODUCTION

The Rotorua Geothermal Field (RGF) is a shallow high enthalpy geothermal reservoir lying directly beneath Rotorua City in New Zealand (Figure 1). It is recognized internationally for its geothermal surface features, and in particular for the geysers and hot springs at Whakarewarewa thermal valley. Whakarewarewa is home Pohutu Geyser which produces large and frequent eruptions and is one of New Zealand's last remaining areas of major geyser activity (Cody, 2007; Figure 1). In total 1570 geothermal features have been identified and referenced across the RGF (Graham *et al.*, 2013; Figure 1). These exhibits a wide range of geothermal phenomena including hot and boiling springs, geysers, silica sinter deposits, mudpools, fumaroles, hot and steaming ground, altered ground and hydrothermal eruption craters (Cody, 2007). The Rotorua Geothermal Field is therefore of great regional, national and international significance. Geothermal features are very sensitive to damage from external factors such as geothermal fluid extraction from an underlying geothermal reservoir. Wells may directly compete with these natural features by extracting water from the same source as supply them. The extraction of fluids from the reservoir also induces a drop in the water levels and reservoir pressures. This causes a reduction in the amount of hot water available to flow to the surface. Boiling alkaline-chloride water springs and geysers derived directly from the reservoir fluids are especially at risk to loss. In addition geysers typically operate at very low pressures, typically < 10 KPa (Cody, 2007). Therefore, a pressure fall of a few KPa may be sufficient to permanently stop boiling at depth and subsequently geysers from erupting (Cody, 2007, Saptadji *et al.*, 2016). Similarly it has been found that most hot flowing springs also operate at very low pressures, typically of only c. 3 KPa (Cody, 2007).

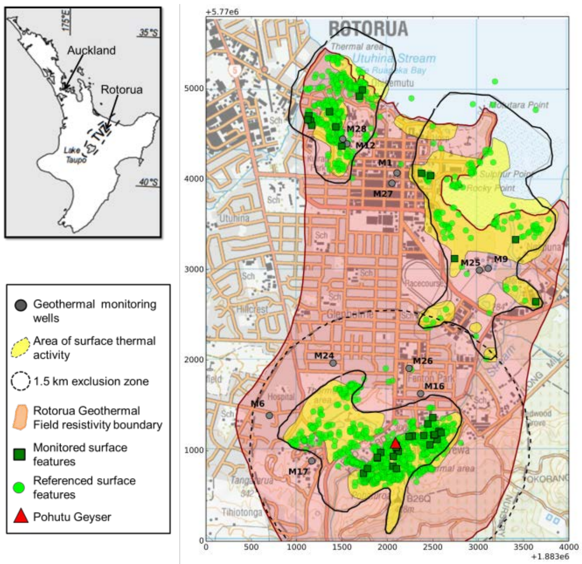

Figure 1: Map of the Rotorua Geothermal Field showing the extent of the field, areas of surface activity, and the locations of geothermal features.

Exploitation of the geothermal waters in Rotorua increased steadily and geothermal bores proliferated from 1950 onwards (Minister of Energy, 1985). By 1986, it was estimated that winter production rates reached a maximum value of 31,150 tonnes per day accounting for approximately 40% of the total outflow from the geothermal field. This was accompanied by a drop in aquifer pressures (Bradford, 1992). This severely impacted on flows of all hot springs and geysers (Cody & Lumb 1992) and resulted in the failure of an increasing number of active surface features from the late 1960s to the early 1980s (Scott *et al.*, 2005):

- The Tarewa Springs became dormant during the 1950s-1970s,
- Kuirau Lake stopped overflowing in the 1970s,

- Waikite stopped erupting in 1967,
- Kereru Geyser stopped erupting in 1972,
- Te Horu Geyser experienced a decline in eruption frequency in 1972 and stopped overflowing in 1987, and
- Papakura geyser last erupted in 1979

To prevent further deterioration of the geothermal features a Wellbore Closure Programme was enforced in 1986. By 1988, it resulted in a 66% reduction in production to 10,830 tonnes per day and a 75% decrease in net withdrawal to 7,150 tonnes per day (Bradford, 1992). It was followed by a fast increase in pressure (0.1–0.2 bar). During the ensuing years recovery of some surface features was also observed.

Forty-one of the most significant features (Figure 1) were selected for monthly temperature, mass flow, and water level measurements from May 2008 (Pearson-Grant *et al.*, 2015) in accordance to the Resource Management Act to “monitor the recovery of geothermal features and protect the surface manifestations while providing allocation of the resource for present and future efficient use” (EBOP, 1999). These include a selection of hot springs, geysers and large pools in five areas of geothermal activity in the RGF: Whakarewarewa (Whakarewarewa Village and Te Puia), Ngapuna, Kuirau Park and Ohinemutu (Figure 1).

A full-scale three dimensional numerical model of the Rotorua geothermal system has been built to replicate the past and current behaviour of the geothermal field and surface features. The aim of this study is to improve the representation of the surface feature in the numerical model. This is to explore the main controls of the surface features at Rotorua, identify long term trends and may serve as a tool to protect the surface features in the future to support the management plan of the geothermal resource.

2. METHODOLOGY

2.1 Conceptual model of an alkaline chloride discharging geothermal surface feature

In geothermal systems in New Zealand geothermal fluids rising from the deepest parts of a geothermal system are typically of near neutral pH chloride composition (Cody, 2007). As these hot fluids reach the upper parts of the system, pressure reduces and boiling may occur. Dissolved gases, particularly carbon dioxide and hydrogen sulphide vaporizes into a vapour phase which then rise independently towards the surface where it may form fumaroles, steaming ground and steam-heated surface features (Cody, 2007). Some of the remaining deep chloride waters may reach the surface, forming features such as boiling alkaline springs and geysers (Cody, 2007). They may also become cooled and diluted, forming dilute chloride waters.

The surface features selected for the monitoring programme and considered in this study are alkaline chloride surface features which best represent the deeper geothermal field and condition in the geothermal reservoir (Pearson-Grant *et al.*, 2015). According to the conceptual model in Figure 2, a geothermal surface manifestation has a feed at a various depth from which the geothermal fluid originates from. The geothermal fluid then flows to the surface through a network of cracks and faults in the rock matrix.

The temperature and overflow or water level measured is therefore directly correlated to temperature and pressure variation of the surface feature feed. Recharge of geothermal fluid from the underlying reservoir as well as rainfall is believed to influence the measured parameters (see Table 1).

These factors are represented in the model by the rainfall injected in the top model block and by temperature and pressure fluctuations in the model blocks at the feed depth.

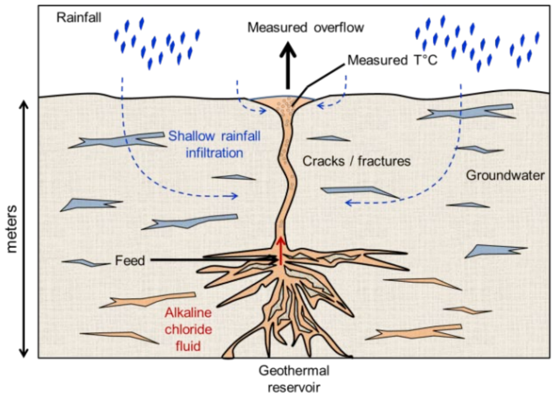

Figure 2: Conceptual model of an alkali chloride discharging geothermal surface feature.

2.2 Method

In previous modelling studies, the surface features were represented by the surface block and the mass flow flowing out into the atmosphere was used (Ratouis *et al.*, 2016). In some cases, where the source of the geothermal features is located at a deeper depth, this may not represent accurately the behaviour of the alkaline chloride surface features. Temperature and pressure fluctuation at the geothermal feature feed may be different than surface condition being influenced by factors of various importance. In addition it may over estimate shallow mixing with the cold overlying groundwater.

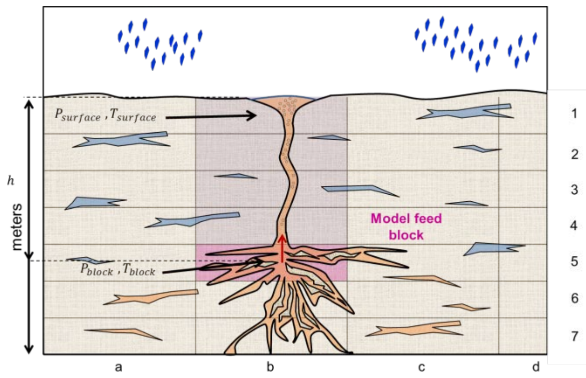

Figure 3: Representation of an alkali chloride discharging geothermal surface feature in a geothermal numerical model.

The method developed here uses the information provided by the history matching simulations to determine the correlation factor between the changes in block enthalpy and pressures and recorded surface temperatures. For every surface features, we extract enthalpy and pressure time series for the first ten blocks in the corresponding column which represent a potential feed locations for the surface feature.

Pearson correlation factors r $_{enthalpy}$ and r $_{pressure}$ between the modelled enthalpy and pressure transients at different depths and recorded temperatures is then calculated. By determining the Pearson correlation factor we aim to quantify the contribution of each block to the surface feature temperature variation and thus identify a potential feed location for the surface features.

A well on deliverability is then implemented in the relevant block to represent the well-like structure of the surface features (feedzone plus vertical high permeability cracks to the surface). The deliverability mode specifies that the flow rate from the features is a function of the reservoir pressure at the feed zone. The formulation of the deliverability option is defined as follows:

$$q = PI \times (P_{block} - P_{cut\text{-}off})$$

Where q represents the mass flow flowing to the surface, PI denotes the productivity index, P_{block} is the pressure in the model feed block, and $P_{cut\text{-}off}$ is the cut-off pressure. This shows that the surface feature will be discharging fluid if the pressure in the feed block is greater than a set pressure, approximated here as the weight of the column of water or hydrostatic pressure:

$$P_{cut\text{-}off} = \rho_{average} gh + P_{atm}$$

Here $\rho_{average}$ is the average density of the column of water, g is the gravity term, h represents the height of the water column, and P_{atm} is the atmospheric pressure.

NUMERICAL MODEL OF THE ROTORUA GEOTHERMAL FIELD

3.1 The Rotorua Geothermal Field

The Rotorua geothermal field encompasses an area of approximately 18 km^2 as defined by temperatures and electrical resistivity measurements (Bibby *et al.*, 1992; Figure 1).

Chemical sampling and downhole temperatures from geothermal bores across the RGF have located three distinct up-flow zones underneath Ngapuna, Whakarewarewa, and Kuirau Park. Faults identified in the southeast section of the field and at Kuirau Park are believed to provide preferential pathways for rising high enthalpy alkaline chloride geothermal fluid. The geothermal fluid flows into the Mamaku Ignimbrite before entering the rhyolite domes toward Lake Rotorua as temperature inversion and increasing HCO3 content suggest (Stewart *et al.*, 1992). The rhyolite and ignimbrite geothermal aquifers are both overlaid by low permeability sediments (Wood, 1992) (Figure 2). This cap is breached where geothermal surface features are evident: Whakarewarewa, Te Puia, Government Garden, Ohinemutu, and Kuirau Park.

3.2 Numerical grid

The mesh structure developed for the numerical model consists of 48,034 blocks in total. It covers an area of 12.4 km × 18.3 km centred on the Rotorua Township with a block size ranging from 125 m × 125 m to 1,000 m × 1,000 m (Figure 5). There are 30 layers (thickness varying from 5 m to 200 m) extending to a depth of 2,000 m below sea level. A total of 120 rock-types were used to account for the geological setting of the RGF (Ratouis *et al.*, 2016).

3.3 Boundary conditions

Constant atmospheric conditions were assigned at the top surface (1 bar, 15°C). Monthly-averaged rainfall is injected in the upper boundary layer as a source term. The lateral boundaries are assumed to be closed. Inflow of high enthalpy water, chloride and CO2 is applied at the base of the model through the inferred faults and a conductive flow of heat of 80 mW/m^2 is applied elsewhere. Time-dependent generation rates are defined bi-annually for the geothermal bores in the RGF from 1950 to 2014 and are included in the history-matching simulations (Ratouis *et al.*, 2016).

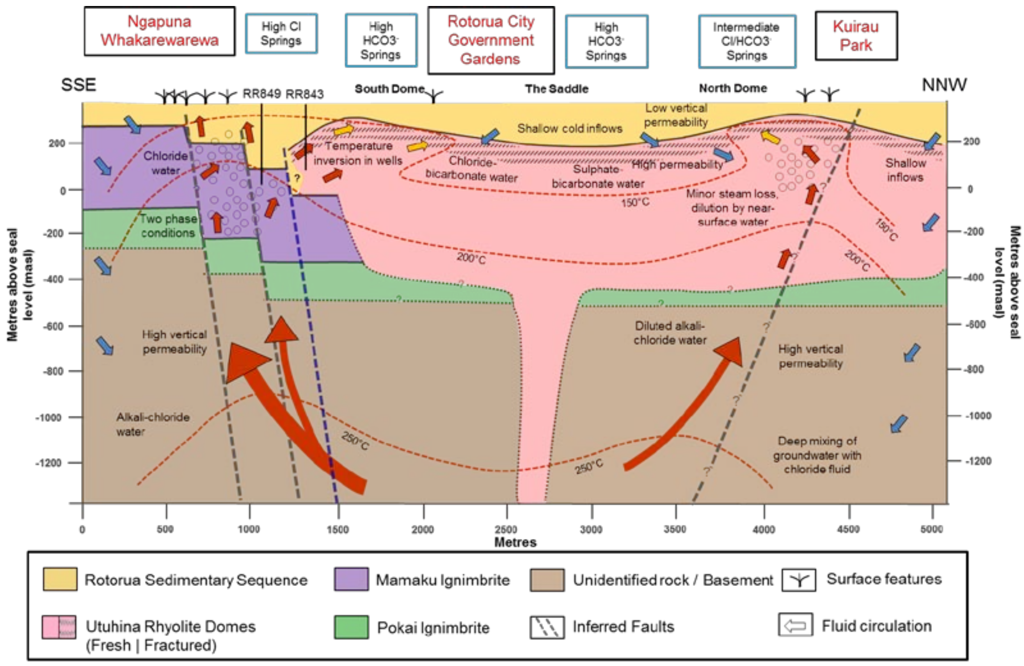

Figure 4: NNW – SSE Cross section of the conceptual model of the RGF.

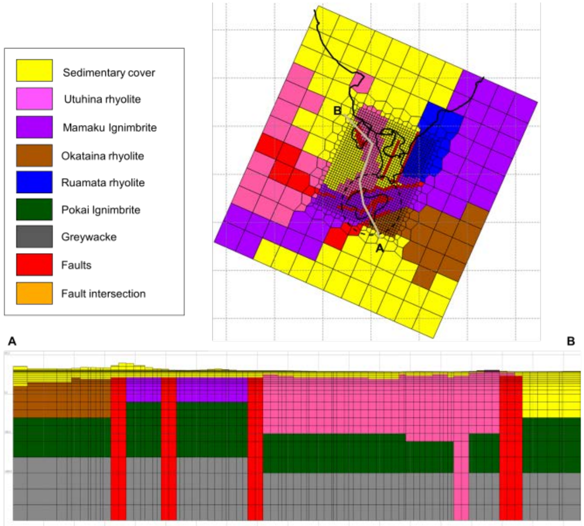

Figure 5: Plan view at 115 masl and vertical cross-section (A-B) of the model, including geology.

3.4 Model calibration

The simulations are run using the numerical simulator AUTOUGH2 (Yeh *et al.*, 2012), the University of Auckland's version of TOUGH2 (Pruess, 1991). The history-matching simulations presented here were calibrated against a wide range of field data; chloride and carbon dioxide concentrations, and pressure transients from monitor wells drilled into the geothermal aquifers (Ratouis *et al.*, 2016). The transient model outputs including the temperature and pressure time series have been found to be consistent with field observations and to replicate conditions in the geothermal reservoir (Ratouis *et al.*, 2016).

4. RESULTS

4.1 Identification of the feed-zone depth

From the history matching simulations the correlation factors between the modelled pressure and enthalpy with the temperature data time series was computed. For blocks located in the two-phase region the weighted enthalpy of the fluid at saturation and saturated gas was calculated. Table 1 shows correlations factors ($r_{enthalpy}$ and p-value) for the surface block and the feed block for a selection of the geothermal surface features considered in this study. Positive correlation factors show that an increase in enthalpies, pressures, or rainfall is linked to an increase in recorded temperatures whereas a negative correlation indicates the opposite behaviour.

Table 1 shows that in the column considered that a block with a higher correlation factor with recorded enthalpies can be found. The depth of the block is different for each surface features and is indicated in the table. These shows the temperature and pressure variations in a deeper block in the column are more closely linked to changes in the recorded temperatures than surface blocks and that this phenomenon is surface feature dependent. The blocks identified using this approach was then used as the location for the wells on deliverability for the simulation results presented below.

For significant correlation factors (p-value < 0.05) temperature and pressure have a positive correlation factor; increases in the measured surface features enthalpy are accurately replicated by increases in model temperature and pressures. In addition rainfall is negatively correlated with recorded enthalpies. An increase in rainfall is linked to a temperature drop in the surface feature. This suggests that there are two competing effects which impact temperature variations in the surface features at Rotorua. That enthalpy variation is caused by a combination of pressure and temperature changes in the geothermal reservoir (replicated to some extent by the numerical model) and rainfall.

Table 1: Pearson correlation factors. Significant correlation factors for p-value < 0.05 are represented in bold. * The p-value tests if the correlation factor is zero.

	Correlation factors	Surface block	Feed block depth
RRF0028			8.5m
	$r_{enthalpy}$	0.425	0.544
	P value	8.542E-05	1.822E-07
	$r_{pressure}$	0.069	0.027
	P value	0.541	0.815
	r_{rain}	-0.297	
	P value	7.421E-03	
RRF0624	Correlation	Surface	13 m
	$r_{enthalpy}$	0.579	0.550
	P value	4.192E-08	2.686E-07
	$r_{pressure}$	0.309	0.416
	P value	6.595E-03	1.837E-04
	r_{rain}	-0.137	
	P value	2.374E-01	
RRF0657	Correlation	Surface	104 m
	$r_{enthalpy}$	0.269	0.220
	P value	0.0203	0.0491
	$r_{pressure}$	-0.249	-0.334
	P value	0.0325	3.617E-03
	r_{rain}	-0.322	
	P value	5.217E-03	
RRF3237	Correlation	Surface	38 m
	$r_{enthalpy}$	0.399	0.517
	P value	9.833E-03	5.445E-04
	$r_{pressure}$	0.113	-0.162
	P value	0.483	0.311
	r_{rain}	-0.217	
	P value	0.173	
RRF0283	Correlation	Surface	7 m
	$r_{enthalpy}$	0.078	0.276
	P value	0.502	0.0159
	$r_{pressure}$	0.181	0.198
	P value	0.118	0.0859
	r_{rain}	0.013	
	P value	0.9	

4.2 Wells on Deliverability

The pressure cut-off and productivity index for each surface features at a given depth is calculated. The history matching simulation is then rerun with the wells on deliverability connected to the feed block (Table 1). Once the simulation is finished flowing enthalpy and generation rates are extracted from the model. The enthalpies are corrected for additional shallow rainfall mixing and atmospheric cooling not taken into account in the reservoir model (Ratouis *et. al., 2016* b). It is written as a function of the enthalpy and mass flow in the corresponding surface block and of the rainfall in the following form:

$$h = \frac{\bar{m}_{rate} h_{flowing} + x\, \bar{m}_{rain} h_{rain}}{\bar{m}_{rate} + x\ \bar{m}_{rain}} - c$$

where h is the corrected enthalpy of the surface feature, $h_{flowing}$ is the flowing enthalpy of the well on deliverability, $\bar{m}_{rate}$ the generation rate of the well on deliverability calculated in the simulation, h_{rain} and $\bar{m}_{rain}$ are the enthalpy and mass flow of the rainfall runoff, x is a calibration parameter representing the dilution due to rainfall runoff entering the surface feature and c is a calibration parameter representing heat losses from boiling, conduction, and radiation (Ratouis *et. al., 2016* b).

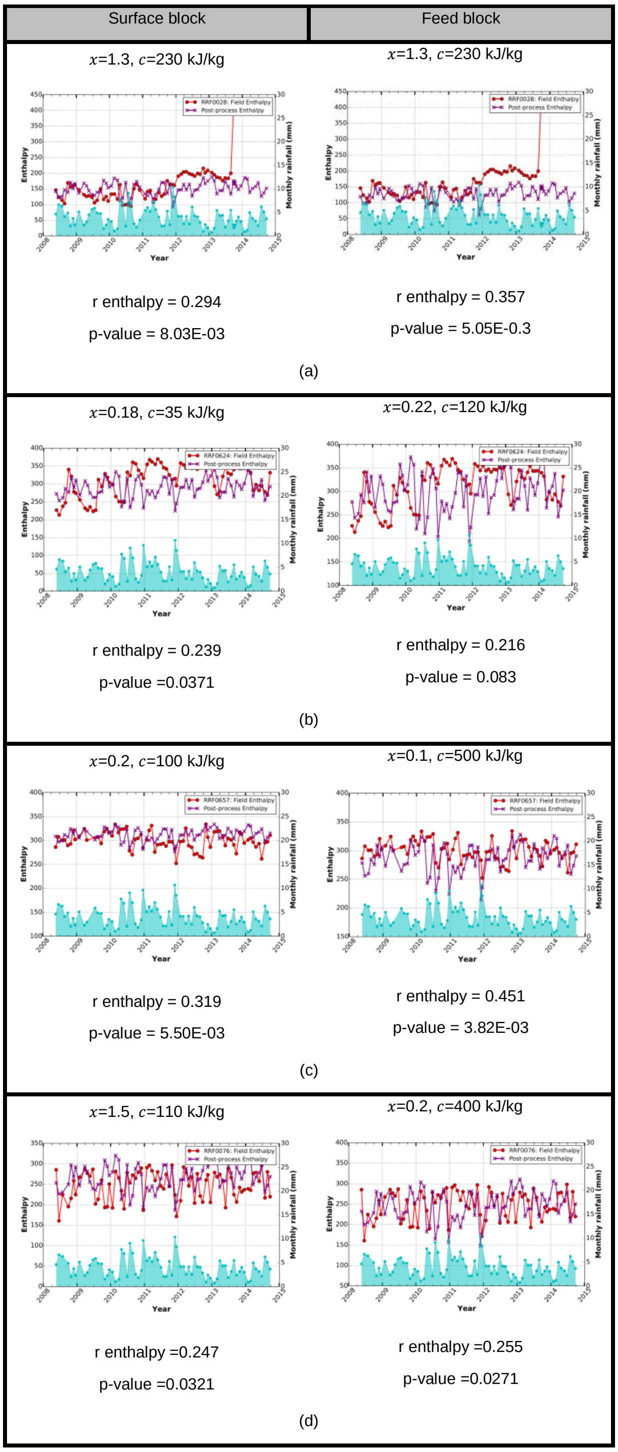

Figure 6: Comparison between the post-processed modeled and measured enthalpy for the surface block and the flowing enthalpy for the well on deliverability. (a) RRF0028 – Papakura geyser. (b) RRF0624 – Soda Spring. (c) RRF0657 – Spring 657. (c) RRF0076 – Te Horu. The dilution factor x and cooling factor c and the correlation factor ($r_{enthalpy}$ and p-values) are indicated.

Figure 6 shows that the correlation factor between the post-processed enthalpies and the recorded enthalpies from the wells on deliverability model are only marginally better than the correlation factor for the surface block. It can be noted that the dilution factor x is smaller while the correction factor c is larger for enthalpies extracted from the well on deliverability than the surface block. It shows that while the flowing enthalpy is hotter, less dilution is required to obtain similar ranges of enthalpy variations with surface features represented by a well on deliverability.

4.3 Papakura geyser

The Monitoring programme shows that four of the surface features monitored at Rotorua experienced a steep change in enthalpies and water level/mass flow variations during the monitoring period: Tarewa Spring in 2009, Fri path in 2010, Waipatuhuka in 2012 and Papakura Geyser in 2013 (Pearson *et al.*, 2016). The current model results and post process enthalpies follow the seasonal variation of enthalpies but fails to reproduce such sudden changes in enthalpies in surface features (Papakura geyser in Figure 6 a). Such shift suggests a sudden change in the dynamic regime of the surface feature.

For example Papakura Geyser experienced in September 2011 a rise temperature which increase from 40°C to 60°C with some boiling observed and an increase in water levels. In September 2013, the temperature rose sharply from 51°C to 94°C and the pool began to over flow. Since, temperatures have gradually increased to boiling point at 98° (Pearson *et al.*, 2016). This indicates a major and sudden change in the behaviour of the surface feature have occured.

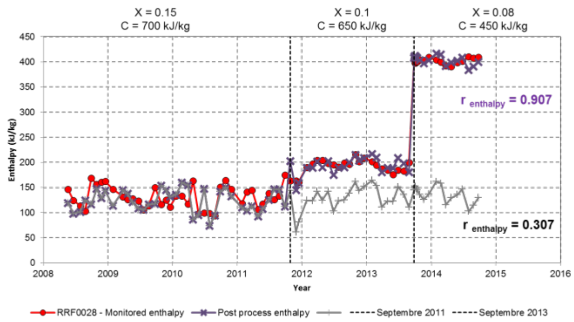

Figure 7: RRF0028 – Papakura geyser. Comparison between a constant and changing post process parameters to represent a change in surface feature behaviour

As stated above the post process flowing enthalpies for Papakura Geyser shows a correlation factor with the measured enthalpies of 0.357 but do not show a steep change in enthalpies.

However if the dilution and cooling factors (x and c) are modified in September 2011 and September 2013 when a change of behaviour have been observed, the post process enthalpies show a near perfect match (Figure 7):

- Prior to September 2011: x = 0.15, c = 700 kJ/kg
- From September 2011 to September 2013: x = 0.1, c = 650 kJ/kg
- From September 2013: x = 0.08, c = 450 kJ/kg

Using these dilution and cooling factor the modelled enthalpies account for 90% of the behaviour of the fluid ($r_{enthalpy}$ = 0.907). This shows that the geothermal fluid at Papakura Geyser has become less diluted by the cold shallow groundwater and rainfall (smaller x and c) and that a higher proportion of geothermal fluid comes directly to the surface. This suggests that an instantaneous event have happened below Papakura Geyser allowing the hot geothermal fluid to flow to the surface. It is possible that pressures below Papakura Geyser have reached a critical value to overcome the pressure from the overlying cold ground water and flow to the surface. In order to model such behaviour a finer model or spring model would be required. Such changes in the characteristics of the surface features could be modelled by a change in the pressure cut off term (column cold ground water lying on top of the geothermal vs. column hot flowing geothermal fluid).

Similar findings have been found for the other three surface features for either an increase or decline in surface activity.

4.3 Soda Spring

Soda Spring (RRF0624) shows a strongly seasonal component in the enthalpy variations (Figure 6 a). Enthalpy highs are usually observed toward the end of the year (2009, 2010, 2011, 2014, and 2015). Additionally the post process enthalpies decrease when big rainfall events are recorded. These decreases are not usually seen in the data (Figure 6 a).

Figure 8 shows the original flowing enthalpy and post-process enthalpy for Soda Spring. Although the post processed enthalpies shows a range of variation similar to the recorded values (Figure 8 a) the match with the data is much closer for the original flowing enthalpy (Figure 8 b).

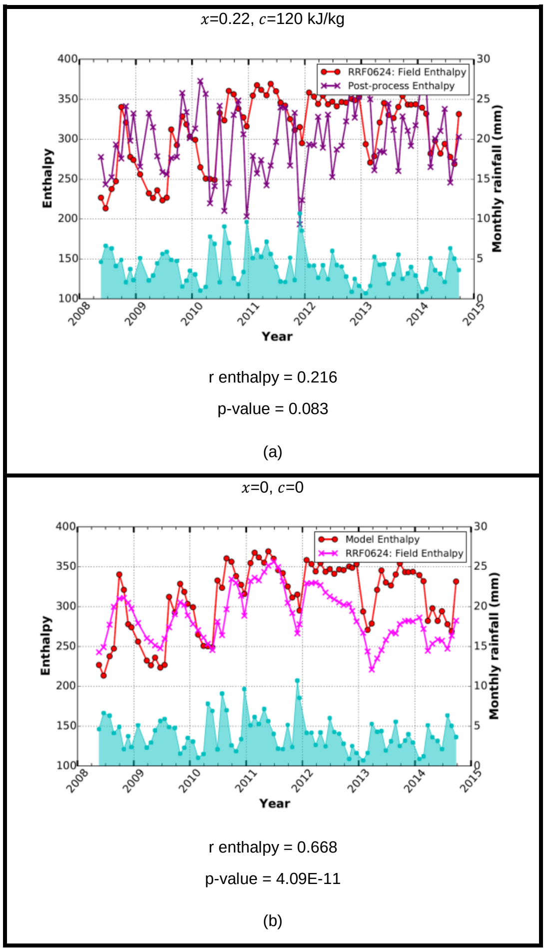

Figure 8: RRF0624 – Soda Spring. Comparison between the post-processed enthalpies and the original flowing enthalpies.

These observations indicate that rainfall does not have a major impact on the behaviour of the surface feature. The variations recorded seem to be controlled by the deeper reservoir which is in turn affected by the recharge of the geothermal reservoir and potentially seasonal production from geothermal bores. A correlation between temperature variations at Kuirau Park (including Soda Spring and Spring 657) and production from neighboring wells was proposed by Soengkono et al., (2001), which seem to be replicated in our model. To achieve a better match to the data, instead of using a simple rainfall mixing tool, a fracture flow, dual porosity model could also be useful for investigating the potential impact of changes in production on the surface features.

4.4 Historical match for wells on Deliverability

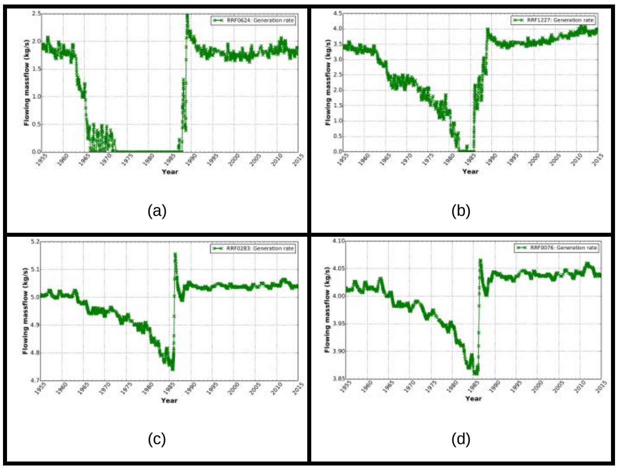

Figure 9: Simulation results showing the enthalpy and the generation rate of the well on deliverability for (a) RRF0624 − Soda Spring at Kuirau Park, (b) RRF1227 – Porahi at Ohinemutu, (c) RRF0283 – Korotiotio at Whakarewarewa, and (d) RRF0076 Te Horu at Te Puia.

Figure 9 shows the simulations results for enthalpy and generation rates for temperatures for the feedzones blocks corresponding to the locations of the feed-zones for the four surface features. Monthly-averaged rainfall is also included.

Although limited field data are currently available for comparison, the model results are consistent with observations that springs at Kuirau Park went dry in the early 1980s. The model shows a full recovery of surface features at Kuirau Park from 1990. This is also consistent with the field observation that these features started discharging in the 1990s with fluids which were chemically similar to those sampled in the 1960s (Mroczek et al., 2004), indicating a recovery to near pre-closure status. A similar behaviour is seen at Porahi in Ohinemutu. For Korotiotio at Whakarewarewa and Te Horu at Te Puia, the simulation results shows a decline in both fluid enthalpy and generation rate prior to the wellbore closure and fast recovery after the closure. Observations at Rotorua suggests that recovery at in Te Puia and Whakarewarewa is not as fast and areas have yet to fully recover from the intensive production prior to the closure. However there are currently no continuous records of surface features from the RGF available for comparison.

CONCLUSION

The aim of this study is to complement and to help interpret the Rotorua monitoring programme data by providing a tool which can identify and replicate spatial and temporal trends of natural and anthropogenic origins.

With that objective in mind wells on deliverability have been successfully implemented into the numerical model of the Rotorua Geothermal Field. The location of the surface feature feed zone have been determined by choosing the block with the highest correlation factor between the variation in temperature and pressure of the block and the recorded data.

This study also shows that by using a numerical model and the extra set of data it provides, we are able to identify some of the mechanisms which control the temperature variations recorded in the geothermal features at Rotorua.

The results are only marginally better however the way of representing the surface feature is more accurate and offer more flexibility by adding two parameters for the wells on deliverability (production index and cut off pressure) which controls the flowing enthalpy and generation of the well.

For Papakura geyser and Soda Spring large changes in the behaviour of the surface features seem to be related to changes in pressure within the geothermal reservoir, more work is needed but this is interesting from a resource planning point of view.

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