MODELLING GEOTHERMAL POWER GENERATION FROM THE WAIOTAPU – WAIKITE – REPOROA GEOTHERMAL FIELDS

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ABSTRACT

The Taupo Volcanic Zone in New Zealand is a cradle of geothermal systems, of which some, such as Waiotapu, are renowned as geo-tourism destinations. Due to its cultural significance, Waiotapu is classified as a protected geothermal system, where no geothermal production is allowed. Geothermal systems with hydrological linkage to Waiotapu such as Waikite and Reporoa are also treated differently than other systems. The Waikato Regional Plan classified Waiotapu – Waikite as protected systems and Reporoa as a research system (Waikato Regional Council, 2019).

The natural state numerical model developed by Kaya et al. (2014) was used to investigate possible strategies from Reporoa area under different production and reinjection scheme for optimum power generation while monitoring the pressure near the surface features to avoid any induced changes in the thermal activity and avoid the adverse effect of development. Investigations were done both on the production side, such as the amount of power generation, location, depth and number of production wells, and also on the injection side, such as the location, depth and number of injection wells, including injection rate. The configuration of production and injection wells was also tested. A monitoring well was located between Reporoa and Waiotapu with the purpose of safeguarding Waiotapu from any potential changes due to production activity.

Based on the test results, the recommended scenario is to set up a 25 MW production in Reporoa, with five production wells and one injection well. The production wells have a maximum steam flow of 47 kg/s from each well, and all injection wells inject both brine and condensate at 100% injection rate. According to our modelling study, the goal of preserving surface manifestations in Waiotapu area is achievable.

1. INTRODUCTION

In this research, the Waiotapu – Waikite – Reporoa (WWR) geothermal systems were analysed to investigate potential scenarios of geothermal power production. It is reported that Reporoa shares a boundary with the Waikite – Waiotapu – Waimangu system and may be linked to them hydrologically (Waikato Regional Council, 2019; Kaya et al., 2014). Although Waiotapu-Waikite is classified as protected systems, the Reporoa geothermal field is classified as "research geothermal system", because there is not enough information in this system to classify it as either "Development", "Limited Development", or "Protected". In these systems, only small takes and those undertaken for scientific research into the system are allowed (Waikato Regional Council, 2019). This study is focused on investigating possible scenarios for geothermal power extraction by considering production and injection activity in Reporoa while closely monitoring the potential impact that it might impose on the Waiotapu area. The outcome of this study will help in understanding the systems better and potentially assist in planning any production that can be considered in this area.

This research was started with a literature survey with regard to the existing conceptual model. The available supporting data were the 3G (Geology, Geochemistry and Geophysics) surveys, downhole temperature measurements and heat loss through surface manifestation information. The pre-existing reservoir model (Kaya et al., 2014) was used to simulate various production and injection scenarios. The objective is to determine the optimum operating conditions needed to maximize the energy recovery by testing different parameters such as power generation capacity, production and injection well location, number and depth, injection rate, and the configuration of production and injection wells.

The modelling was undertaken by using EOS1 (pure water) module of AUTOUGH2 (Yeh et al., 2011; Yeh et al., 2012), The University of Auckland version of TOUGH2 (Pruess et al., 1999), and the visualisation was performed by using TIM (Yeh et al., 2013). Production and injection wells on the deliverability functions were used in the AUTOUGH2 parameterization. Test results were assessed based on the pressure history at selected locations and the amount of power generation throughout 30 years of production.

2. WAIOTAPU – WAIKITE – REPOROA NUMERICAL MODEL

The three-dimensional steady-state numerical model parameters developed by Kaya et al. (2014) are summarized in Table 1, and the area coverage is shown in Figure 1.

Table 1 Summary of WWR numerical model parameters

Parameter	Details
Area coverage	450 km^2
Regular rectangular grid	57 x 57 blocks
Model depth	600 mRL - 3000 mRL
Smallest grid block size	250 m x 250 m
Layers	16 layers
Total grid blocks	51426 grid blocks including the atmospheric block
Water table levels	295 mRL to 623 mRL
The base of the model	–3000 mRL (to include greywacke basement)

In this model, thermal conductivity of 2.5 W/mK was used, by considering a vertical temperature gradient of ~ 30 °C/km, and therefore a heat flux of 0.08 W/mK was assigned to represent the background terrestrial heat flow. In addition, deep sources of hot water were assigned at the base of the model at -3000 mRL to represent sources of thermal

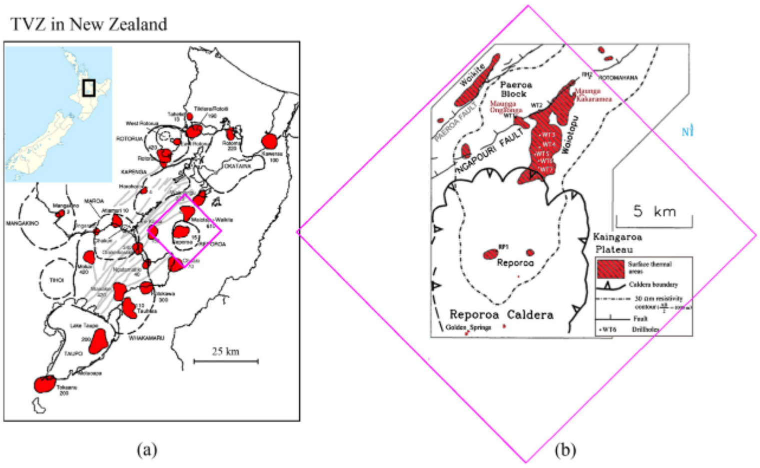

Figure 1 (A) Map of TVZ highlighting the geothermal fields (red), caldera location (dashed lines) and Taupo Fault Belt (grey lines). (B) Location of Waiotapu, Waikite and Reporoa geothermal fields in TVZ (Kaya et al., 2014). The pink square represents the areal extent of the analysis area in this study.

fluid. The values should not be seen as a tight constraint as there is a considerable amount of uncertainty in the estimate of surface heat. The top of the model was set following the water table. Very large artificial wet atmospheric blocks were assigned with temperature and pressure values fixed at atmospheric condition, which corresponds to a pressure of 1 bar and a mean annual temperature of 15 °C. The shallow unsaturated zone was not included in the model. The topmost boundary of the model also allows water and/or steam to flow freely out of the model and water can flow into the model. To represent surface outflows to hot pools and hot springs, spring wells with constant mass flow rate were included beneath the inferred cap rock, centred at -100 mRL, corresponding to the sixth layer in the model. The flow rate specified for the spring well in the model is for the 100 °C geothermal water only. Cooler water also flows out of the top block in the model. The summation of these two flows needs to be matched with the field data representing surface manifestations. The model was built with a large size, thereby the recharge outside later boundaries of the model is considered negligible and therefore considered as no-flow boundaries.

3. PRODUCTION & INJECTION EXPERIMENTS

3.1 Production and Injection Model Scenarios

The tests were started from the production scenario investigation to the injection scenario investigation and then based on the key findings from these two aspects, the combination of production and injection scenarios was further refined.

Since the scenarios are simulations of the future outcomes, production and injection wells on deliverability functions were used in the parameterisation, which specifies that the flow rate from the well will decline as the reservoir pressure at the feed-zone declines. For all production wells, the DELT option was used in AUTOUGH2 to allow discharge proportional to the pressure above some cut-off pressure value. For the injection wells, the PINJ option was used in AUTOUGH2 to allow a fraction of production from a group of wells to be injected into an injection well. The test catalogue is provided in Table 2. Figure 2 depicts the area tested for the location of production wells, with respect to the location of the Waiotapu area. Detailed parameterisation is shown in Table 3 and Table 4.

Table 2 Test catalogue of the investigation of production and injection scenarios in Reporoa area.

Test No.	Scope of test	Main attribute	Scenario
1	Power generation	Maximum steam flow per well and the number of wells	a. 10 MW b. 20 MW c. 25 MW d. 30 MW
2	Production depth	Production layer	a. Layer 9 b. Layer 11 c. Layer 13
3	Well location	Injection block location	a. 2 wells NE b. 2 wells SE c. 2 wells SW d. 2 wells NW
4	Well number	Number of injection wells	a. 1 well (boa 12) b. 1 well (brj 12) c. 2 wells (boa 12 & brj 12)
5	Injection depth	Injection layer	a. Layer 9 b. Layer 11 c. Layer 12 d. Layer 13
6	Injection rate	Injection rate (water & condensate)	a. 50% b. 75% c. 100%
7	Power generation & injection combination	Maximum steam flow per well and the number of wells	a. 10 MW b. 20 MW c. 25 MW d. 30 MW

The temperature of injectate is an important parameter to consider when determining injection parameters since it is closely linked to the silica saturation index. In this investigation, the temperature of injected water is 180 °C corresponding to the enthalpy of 763.2 kJ/kg, and the temperature of injected condensate is 40 °C, corresponding to the enthalpy of 167.5 kJ/kg.

Productivity index is also an important parameter that have a strong influence on the results. We assumed a slightly conservative on the low side productivity index (Kaya, 2010) of 1.0 10 $^{-12}$ m^3 for the wells to ensure reliable assessment of the power generation potential.

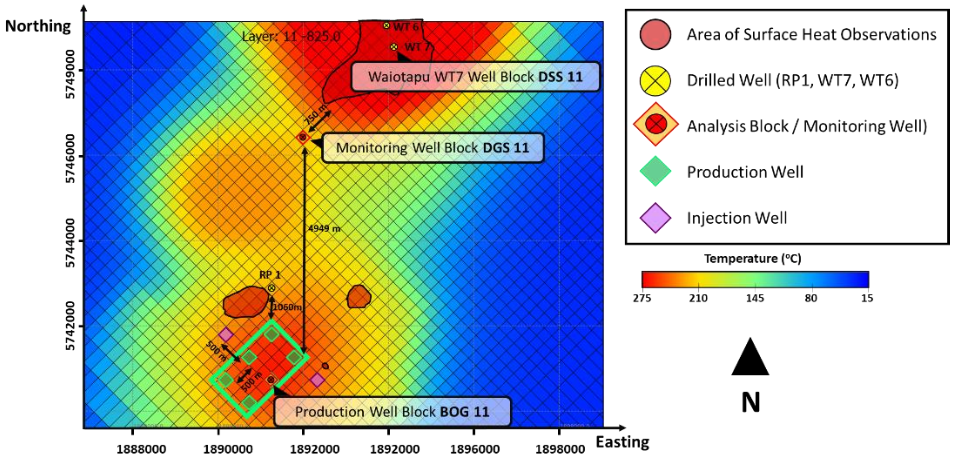

Figure 2 Areal structure of WWR numerical model showing the region for geothermal power production in Reporoa (green rectangle) and three main blocks to assess test scenarios which are bog 11, dgs 11 and dss 11. The distance of block dgs 11 to the production region is approximately 5 km while the distance of block dgs 11 to Waiotapu surface features is 750 m.

Table 3 Parameterisation of Test 1 – Test 4. Yellow color highlights the parameter differences.

Parameter		Test 1 Power Generation				Test 2 Production Depth			Test 3 Injection Well Location				Test 4 Injection Well Number		
		a	b	c	d	a	b	c	a	b	c	d	a	b	c
Generated power (MW)		10	20	25	30	30			30				30		
Production	Number of wells	2	4	5	6	6			6				6		
	Block names	bog, bod	bog, bod, brg, brd	bog, bod, brg, brd, blg	bog, bod, brg, brd, blg, bld	bog, bod, brg, brd, blg, bld			bog, bod, brg, brd, blg, bld				bog, bod, brg, brd, blg, bld		
	Layer	11				9	11	13	11				11		
	Depth (mRL)	- 825				-525	-825	-1350	- 825				- 825		
Injection	Number of wells	1				1			1				1	1	2
	Block names	brj				brj			bud	brj	bid	boa	brj	boa	brj boa
	Layer	12				12			12				12		
	Depth (mRL)	- 1050				- 1050			- 1050				- 1050		
DELT	Max. total flow per well (kg/s)	46.5				46.5			46.5				49.5		
	Productivity index	$1e^{-12}$				$1e^{-12}$			$1e^{-12}$				$1e^{-12}$		
	Cut-off pressure	40				40			40				40		
PINJ	Injectivity index	$1e^{-12}$				$1e^{-12}$			$1e^{-12}$				$1e-^{12}$		
	Water enthalpy	763.2				763.2			763.2				763.2		
	Water temperature	180				180			180				180		
	Condensate enthalpy	167.5				167.5			167.5				167.5		
	Condensate temperature	40				40			40				40		
	Water and condensate injection rate (%)	100				100			100				100		

Table 4 Parameterisation of Test 5 – Test 7 and the final selected parameters. Yellow color highlights the parameter differences.

Parameter		Test 5 Injection Depth Test				Test 6 Injection Rate			Test 7 Power & Injection Combination				Final Parameter
		a	b	c	d	a	b	c	a	b	c	d	
Generated power (MW)		30				30			10	20	25	30	25
Production	Number of wells	6				6			2	4	5	6	5
Production	Block names	bog, bod, brg, brd, blg, bld				bog, bod, brg, brd, blg, bld			bog bod	bog bod brg brd	bog bod brg brd bld	bog bod brg brd blg bld	bog, bod, brg, brd, blg
Production	Layer	11				11			11				11
Production	Depth (mRL)	- 825				- 825			- 825				- 825
Injection	Number of wells	2				2			2				2
Injection	Block names	brj boa	brj boa	brj boa	brj boa	brj boa			brj boa				brj, boa
Injection	Layer	9	10	12	13	12			12				12
Injection	Depth (mRL)	-525	-675	-1050	-1650	-1050			-1050				- 1050
DELT	Max. total flow per well (kg/s)	49.5				49.5			46.5	46.5	47	49.5	47
DELT	Productivity index	$1e^{-12}$				$1e^{-12}$			$1e^{-12}$				$1e^{-12}$
DELT	Cut-off pressure	40				40			40				40
PINJ	Injectivity index	$1e^{-12}$				$1e^{-12}$			$1e^{-12}$				$1e^{-12}$
PINJ	Water enthalpy	763.2				763.2			763.2				763.2
PINJ	Water temperature	180				180			180				180
PINJ	Water injection factor	1				1			1				1
PINJ	Condensate enthalpy	167.5				167.5			167.5				167.5
PINJ	Condensate temperature	40				40			40				40
PINJ	Condensate injection factor	-1				-1			-1				-1
PINJ	Water and condensate injection rate (%)	100				50	75	100	100				100

3.2 Assessments Aspects

1. Pressure Histories

   For the reservoir pressure histories, representative grid-blocks were chosen for each area. For example, block "bog 11" represents the production area, which is selected to observe the impact of various scenarios on the pressure of the production area. Block "dgs 11" represents the monitoring well, which is selected to have early detection of the impacts of production activity before reaching the Waiotapu area. Block "dss 11" represents the Waiotapu area, which is selected to check the impact of power production from the Reporoa area. The location of these blocks is depicted in Figure 2. The pressure histories obtained from applying a certain scenario will be compared against the pressure histories obtained from the natural state model run without applying any production or injection, which is termed as "baseline". The goal is to choose an optimum production and reinjection strategy, which results in the least deviation of pressure history with respect to the baseline scenario.

2. Generated Power & Enthalpy Efficiency

   Varney et al. (2017) conducted a study showing that enthalpy efficiency can be utilized for resource assessment of geothermal fields, as it is superior in terms of comparability across different geothermal sites while satisfying homoscedasticity. By using the enthalpy efficiency data and linear regression technique, a logarithmic line of best fit below was obtained

$$\eta_{enthalpy} = 7.619 \ln(h_r{}^{GThF}) - 44.066$$

Here $\eta_{enthalpy}$ is the enthalpy efficiency, and h_r^{GThF} is the specific enthalpy of the geothermal fluid in a reservoir. The enthalpy efficiency equation above was used to calculate the power generation from the scenarios tested in this study.

4. TEST RESULTS

4.1 Parameter Analysis

1. Production Parameters

   The number of production wells to generate the desired power generation, including the well locations and the level of production zone were tested. Existing natural state model's heat profile, horizontal permeability and vertical permeability were considered while deciding the locations and depths of the wells. The findings are as follows:

   - Regarding the power generation, the maximum steam flow per well and the number of wells were tested to achieve different power generation scenarios of 10 MW, 20 MW, 25 MW and 30 MW (Figure 3). All scenarios exhibit a power generation decline within the range of 0.22 MW to 2 MW, with 10 MW scenario experiencing the least decline and 30 MW scenario experiencing the most decline. It was also found that all of the scenarios exhibit enthalpy efficiency values within the range of 9.12 to 10 %.

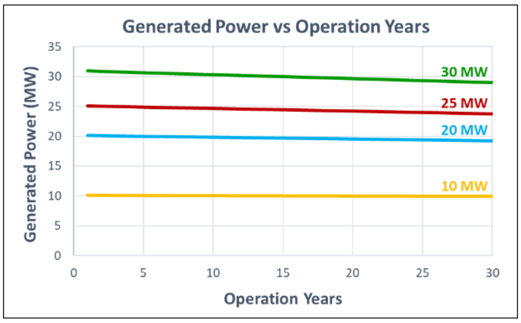

Figure 3 Plot of generated power throughout the operation years.

   - Regarding the production depth, the layer from which production activity takes place were tested for three different layers: layer 9 (-525 mRL), layer 11 (- 825 mRL) and layer 13 (-1350 mRL) as shown in Figure 4. It was found that production from layer 11 (above injection layer) and layer 13 (below injection layer) exhibit almost similar values of power generation and enthalpy efficiency, while production from layer 9 exhibited a considerably lower power generation and enthalpy range due to the distance between production and injection elevations (Figure 5).

   The investigation is conducted for a time period of 30 years ahead, which is a time period that is not allowed by the regulation. Therefore, although power production in this area is unfeasible due to provisions in regulations, the outcome of this study will help to understand the WWR system better, and potentially aid in any research or development plan that can be conducted in this area.

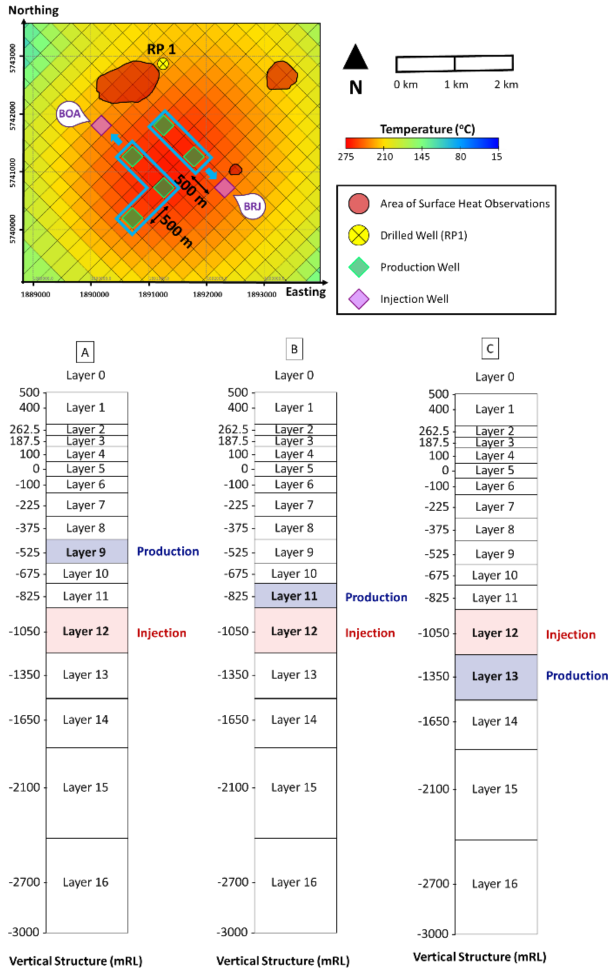

Figure 4 The aerial and vertical view of production and injection well blocks overlaid on the map of the temperature distribution in layer 11 (Top). Different production and injection layers were tested (A, B, C).

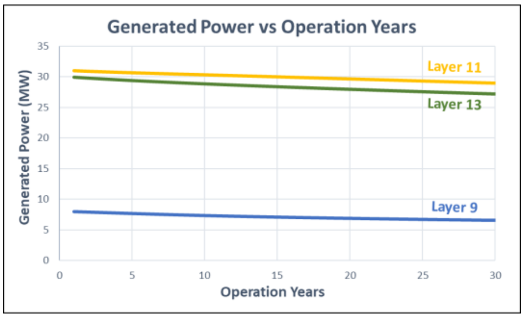

Figure 5 Plot of generated power over the operation years from different production layer scenarios.

2. Injection Parameters

   In the injection parameter tests, the number of injection wells required to ensure adequate energy recovery and balance of system, the location of these wells, injection rates and the depth of reinjection were tested. Existing natural state model's heat profile, horizontal permeability and vertical permeability were considered while deciding the injection well locations and depths. The findings are as follows:

- Regarding the injection well location, injecting water and condensate to the northern area in general increases the pressure in Waiotapu, while injecting water and condensate to the southern area in general causes the pressure in Waiotapu to drop (Figure 6).

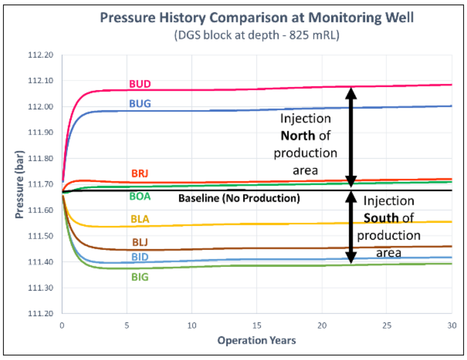

Figure 6 Plot of pressure history at the monitoring well, showing the difference between locating the injection well to the northern area compared to the southern area.

- Regarding the number of injection wells, having two injection wells results in fewer pressure changes with regard to the baseline, unlike when only one injection well is used.
- Regarding the injection well depth, different injection layers were tested, and it was found that injection into layer 9 shows the most pressure drop compared to others. This is due to low vertical permeability assigned to the Wairoa formation within that region on layer 10, which prevents the hydraulic connection between shallow and deep levels of the Reporoa reservoir. The injection layer that shows the least deviation with regards to the baseline scenario is injection to layer 12, which corresponds to the depth of – 1050 mRL. This result is illustrated in Figure 7.

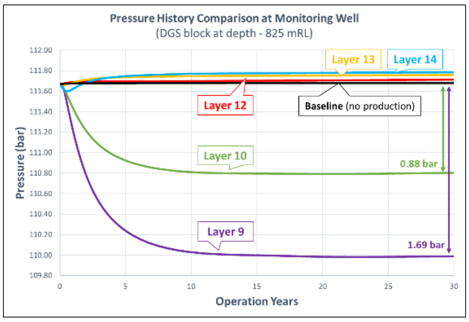

Figure 7 Pressure history comparison at monitoring well showing the results of different injection layer scenarios.

- Regarding the injection rate, it was found that the injection rate of 50% would not give enough pressure support to the production scheme, shown by the observed pressure-drop of 0.45 bar. Compared to an estimation of 4 bar pressure change over 50 years in Rotokawa field (Hernandez et al., 2015), the 0.45 bar value is considerably small. However, due to the high uncertainty of other parameters, it is safer to choose the scenario which has the lowest impact on the pressure histories of monitoring well. The injection rate of 75% and 100% showed almost similar trends. Injection of 100% water and condensate might be more preferred since it would be theoretically safer for the environment. This result is shown in Figure 8.

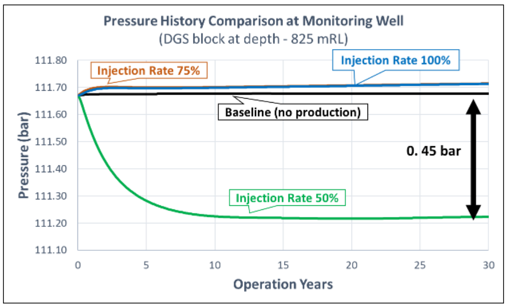

Figure 8 Pressure history comparison at monitoring well showing the results of different injection rates.

3. Production and Injection Combination

   To decide the parameters that result in an optimum power development strategy, two main tests performed; the power generation and the configuration of production and injection wells. The findings are as follows:

- Regarding the power generation, the pressure history at dgs monitoring block at a depth of -825 mRL is shown in Figure 9. With regards to the maximum pressure change from the baseline, 30 MW scenario shows the maximum change of 0.043 bar, while 25 MW scenario shows the minimum change of 0.013 bar. It should be noted that the pressure drop of 0.043 is insignificant, and according to our model, power generation up to 30 MW does not have a considerable effect on the pressure of the monitoring block. However accounting for the likely size of model-related uncertainties, we chose 25 MW option, which results in the least amount of pressure change.

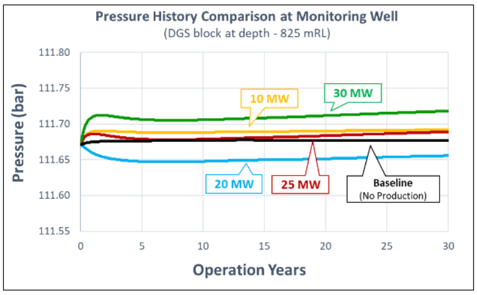

Figure 9 Pressure history comparison at monitoring well showing the results of different power generation scenarios.

- Regarding the production and injection well configuration, different configurations result in negligible changes in the pressure history, power generation and enthalpy efficiency. In this case, the final decision was heavily based on maintaining the pressure history in the monitoring block area rather than the overall performance of the production activity. However, this trade-off would vary depending upon the objective of drilling.

4.2 Final Parameters

The final parameters are shown in Table 4, and the layout is depicted in Figure 4. In the process of parameter selection, the following assessment methodology was applied by considering the results shown in Figure 10:

- At the monitoring block dgs 11, pressure histories in the deeper level (- 825 mRL) and shallower level (- 100 mRL) were compared to the pressure history of the baseline scenario where no production activities occur. It can be seen in Figure 10 (A) and (B) that the difference between the pressure histories with respect to the baseline at year 30 is only 0.0013 bar for the assessment in deeper level, and 0.0017 bar for the assessment in shallower level. These values are considerably small, which means that the production activity made negligible pressure change to this area.

- At the production block bog 11, pressure histories in the deeper level (-825 mRL) and shallower level (-100mRL) were compared to the pressure history of the baseline scenario. It can be seen that the difference between the pressure histories with respect to the baseline at year 30 is only 6.157 bar for the assessment in deeper level, and 0.07 bar for the assessment in shallower level. The more significant drop in the deeper level is expected since that block and layer were exactly where the production is assigned. These values are considerably small which means that the production activity made negligible pressure change to this area, particularly after the production parameters are combined with a suitable injection scheme derived from a series of reinjection scenario tests.
- At block dss 11, pressure histories in the deeper level (-825mRL) and shallower level (-100mRL) were compared to the pressure history of the baseline scenario. It can be seen that the difference between the pressure histories with respect to the baseline at year 30 is only 0.0011 bar for the assessment in deeper level, and 0.0058 bar for the assessment in shallower level. These values are considerably small, which means that the production activity made negligible pressure change to this area.
- Based on the generated power versus operation year chart, the difference between the generated power in year 1 and year 25 is only 1.37 MW, showing that there is no drastic change of power generation from year 1 to year 30.
- Based on the enthalpy efficiency plot, the enthalpy efficiency ranges from 9.25 to 9.49 % and the enthalpy ranges from 1094.31 to 1128.74 kJ/kg.

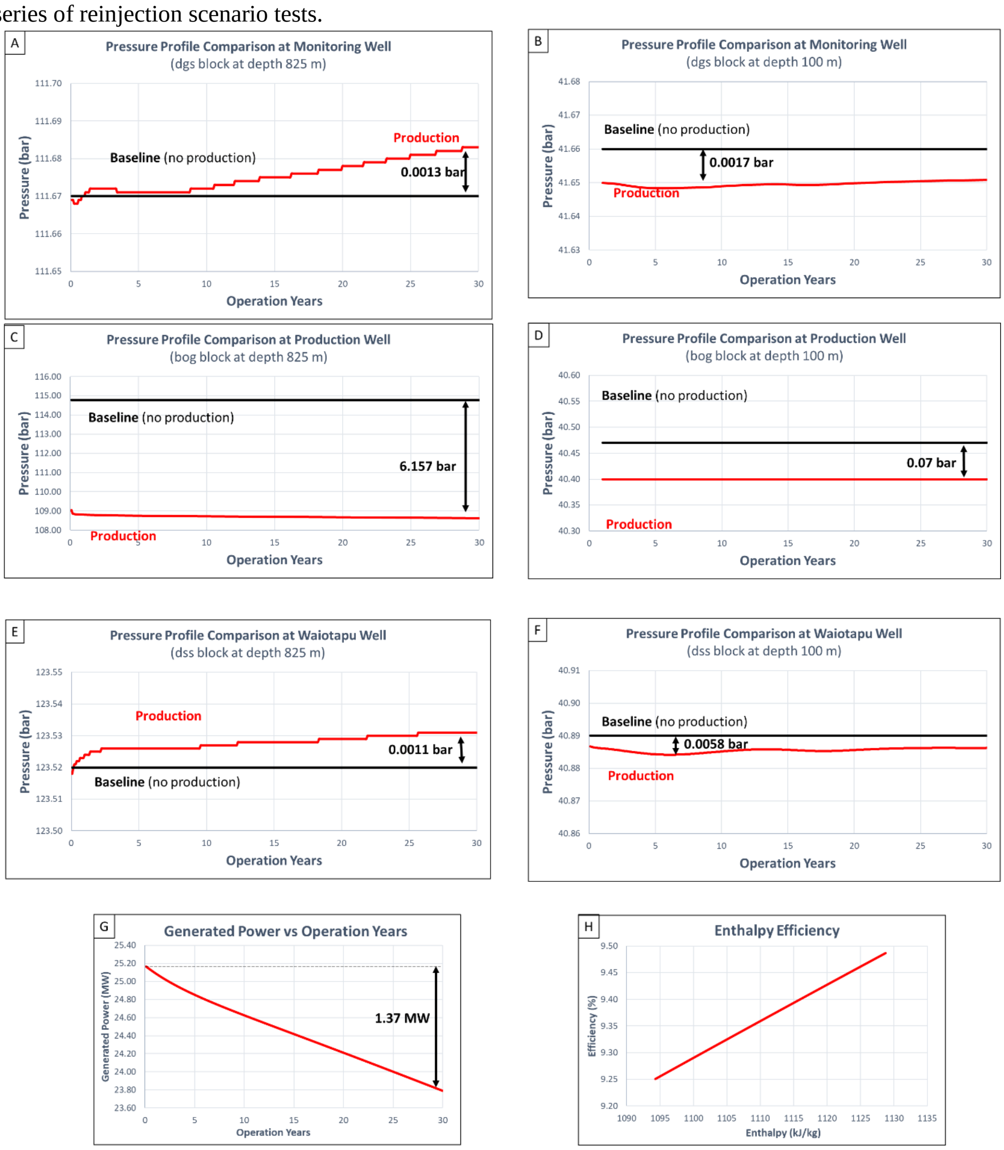

Figure 10 Assessment results on the final selected parameters. (A) Pressure histories in production block dgs at -825 mRL depth and (B) -100 mRL depth. (C) Pressure histories in monitoring block bog at -825 mRL depth and (D) -100 mRL depth. (E) Pressure histories at block dss at -825 mRL depth and (F) -100 mRL depth. (G) The generated power versus operation years and (H) enthalpy efficiency.

5. CONCLUSIONS

The final recommended power generation scenario has been determined, whereby the production is centred in Reporoa with a target of 25 MW, achieved with five production wells and one injection well. All production wells have a maximum steam flow of 47 kg/s, and the injection wells inject both water and condensate at 100% injection rate. With this scenario, assessments on pressure histories in different blocks such as a production block in Reporoa, a monitoring block located between Reporoa and Waiotapu, and a block in Waiotapu showed that the limited production activity in Reporoa causes a negligible impact on Waiotapu system. Therefore, according to our modelling study, the goal of conducting a power generation in Reporoa, while preserving surface manifestations in Waiotapu area, is achievable.

However, it should be noted that considering the Waiotapu system is a natural heritage and culturally significant, we only tried up to a 30 MW power generation scenarios and implemented conservative assumptions (i.e. low productivity index, minimum pressure change allowance in monitoring wells) into our model. Also, the model utilized in this study was calibrated with sparse natural state data, and no production has been commenced in the field. These "partially calibrated" models require more external assumptions to be made because data are limited while the structure of the geothermal field is complex. The accurate prediction of these simulations depends on the uncertainties associated with the reservoir parameters used as well as the production and injection on deliverability function used in the parameterisation. As more natural state and production data becomes available, permeabilities and porosities can be calibrated further by checking the predicted pressure changes and the predicted production enthalpies. The presented assumptions may not be as satisfactory, but they are the only practical alternative for our interpretations.

The results presented in this study are based on forward modelling analysis, where the estimate is based on the model parameters. The investigation could be improved further by focusing on the optimisation of the modelling parameters, especially the rock permeabilities, by using inverse modelling technique powered by Parameter Estimation (PEST) software. Since one of the tasks of this reservoir modelling is to establish whether the pressure changes can be avoided if a certain management strategy is undertaken, the uncertainty analysis process can be extended to consider the management actions, accompanied by the proposal of a hypothesis that includes pressure changes in the Waiotapu area. The rejection of that hypothesis can then provide a better assessment at a certain level of confidence. This can be achieved by using PEST uncertainty utilities.

Although power production in this area is currently not considered due to limitations stated by the provisions in the Waikato Regional Plan, the outcome of this study is beneficial to estimate the system's resource capacity, and potentially aids in any research and development plan that can be conducted in this area.

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