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# Chloride Model of Ngatamariki Geothermal System

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## ABSTRACT

The Ngatamariki geothermal field in the Taupo Volcano Zone of New Zealand provides power to a full binary 82 MWe net plant commissioned in 2013. Over its 7 years of production, the plant and production wells have observed stable enthalpy. The field has shown stable pressure after an initial small drawdown following plant start-up in its reservoir monitoring wells. To search for any indication of future changes in the field, the chemistry of the produced fluid is inspected. The chloride concentration is slightly diluting.

The Ngatamariki numerical reservoir model has been improved to include chloride data. A new method is used and described here. TOUGH3 is used for the reservoir simulator and is coupled with a wellbore model. TOUGH3 allows for faster modelling than TOUGH2 due to its ability to run in parallel. EOS1 with two water components is used as a tracer for chloride concentration. Fresh water in shallow aquifers is water #1. Geothermal upflow rich in chloride is water #2. Pressure, temperature, and chloride concentration are modelled throughout the reservoir and wellbore. The model is calibrated to latest production data and new information from drilling.

The process of calibrating the model to the latest data has led to greater understanding of the geothermal system. The model is calibrated to match shut PTS, flowing PTS, quarterly chloride concentrations, continuous downhole pressure, and plant enthalpy. Learnings are described regarding the temperature distribution and flow paths within the reservoir. The dilution trend is captured in the model to improve forecasts of future production, and therefore, the updated model allows for better resource and risk management.

## 1. INTRODUCTION

### 1.1 Background on Ngatamariki Geothermal Field and Ngatamariki Reservoir Models

The Ngatamariki geothermal field is located in the Taupo Volcano Zone (TVZ) of New Zealand. Four exploration wells were drilled in 1984 at Ngatamariki by the New Zealand government. Exploration surveys were completed and three additional wells were drilled in 2008-2009 (Boseley et al., 2010). A binary 82MWe net plant was commissioned on the field in 2013. Today, the plant has a consented take limit of 60,000 t/d of geothermal fluid. All produced fluid is re-injected, besides minor losses. The hot reservoir is a compressed liquid of temperatures up to 280-290°C. Gas content is less than 0.3 wt%, of which ~95% is $CO_2$. The power plant is currently supplied by three production wells in the center of the field: NM7, NM12, and NM13 (Figure 1). The plant uses four injection wells: NM6 and NM10 in the south and NM8 and NM9 in the north.

A few reservoir models have been developed to describe the pressures and temperatures of the Ngatamariki geothermal field to plan for future electricity generation. Initially, a single porosity TOUGH2 numerical reservoir model was created before field development with 33,966 elements (Burnell and Kissling, 2009). A dual-porosity model of 13,156 elements was built in 2010 to more accurately represent cooling risk from an overlying aquifer (Burnell, 2010). Dual-porosity is implemented through multiple interacting continuum (MINC) (Pruess, 1992) with a fracture volume fraction of 1% (Quinao and Zarrouk, 2015). Process models were made to constrain sensitivity to fracture spacing and reservoir size (Clearwater et al., 2012). An improved full field model was developed using iTOUGH (Moon et al., 2014).

### 1.2 Production History Data from Ngatamariki and Reason for Chloride Model

The Ngatamariki field has been producing since 2013. Over this time, the field has appeared healthy. No sign of decline has been observed in reservoir pressure or plant enthalpy. Following plant start-up, a small drawdown of less than 3 bar was observed in monitoring well NM3. Since then, the field has shown stable pressure as observed through continuous measurement with pressure tubing (Figure 2). Pressure is measured at the pivot point of the well at -1150 m elevation.

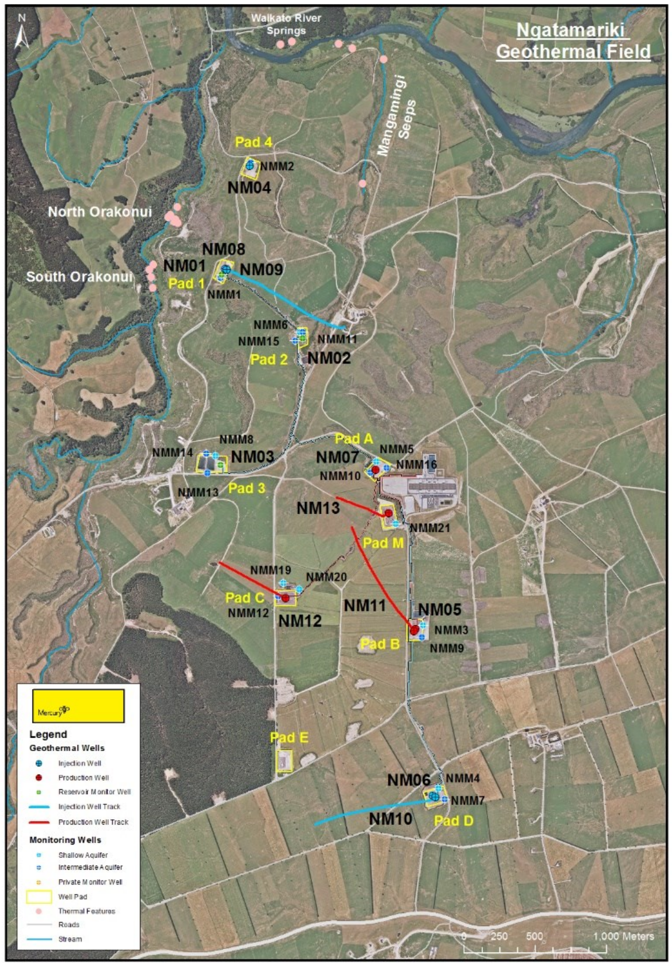


**Figure 1: Map of Ngatamariki geothermal field**

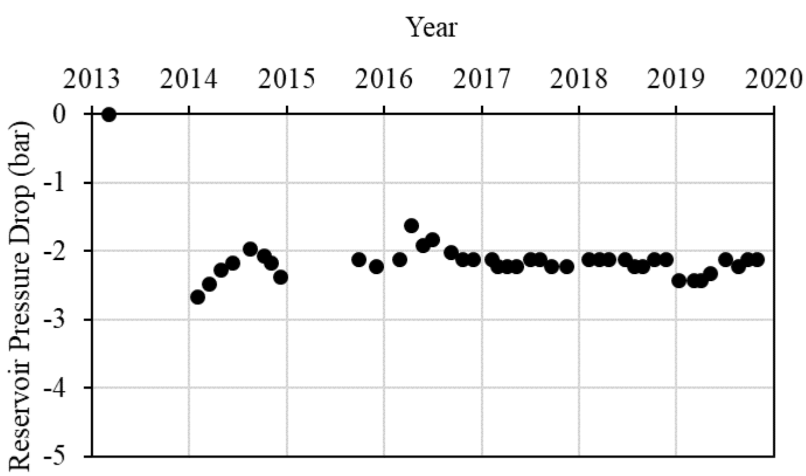


**Figure 2: Reservoir pressure drawdown**

All production wells at Ngatamariki have observed stable enthalpy (Figure 3). Flowing PTS (pressure, temperature, spinner) surveys are used to determine the enthalpy of individual wells. The temperature of the liquid downhole is measured at the casing shoe, which is below the flash depth. Enthalpy observed at the plant has also been stable (Figure 4). Transitioning from lower enthalpy wells to higher enthalpy wells caused the observed enthalpy at the plant to slightly increase during the first few years of production. The enthalpy at the plant is calculated from the measured steam and brine flows at the plant separator.

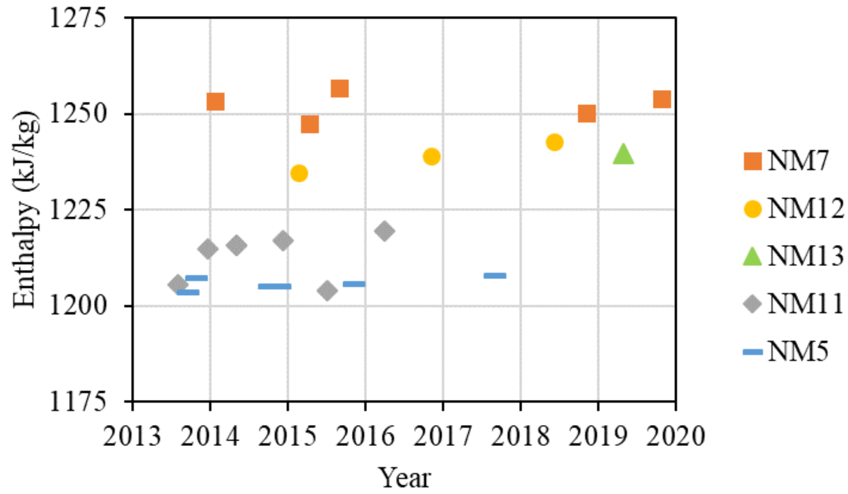


**Figure 3: Enthalpy of production wells**

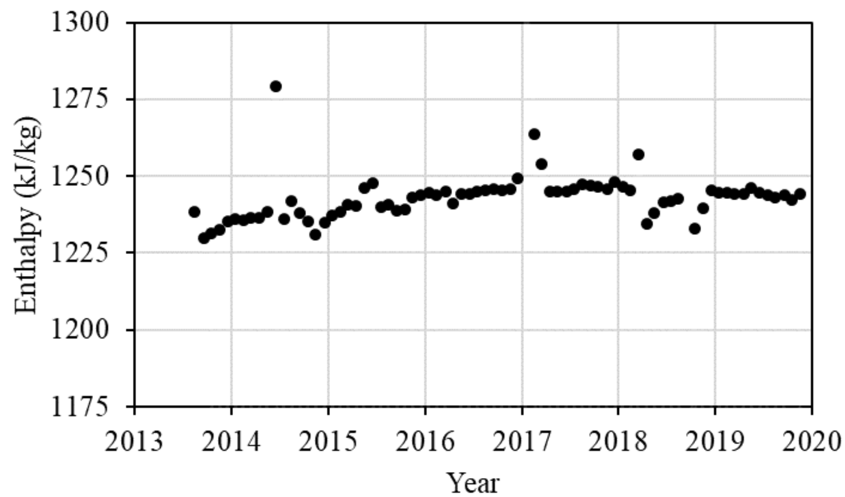


**Figure 4: Plant enthalpy**

All data from the field is inspected for any sign of future changes to come to prepare for any possible risk to reservoir pressure or production enthalpy. One potential sign of future enthalpy decline is revealed by analysis of the chemistry trends of the produced fluid. The chemistry of the produced fluid is sampled on a quarterly basis during tracer flow testing (TFT). The chloride trends in particular have shown signs of dilution beginning in 2016 (Figure 5). Initially there were variable concentrations of chloride among the wells, with NM11 having the lowest concentration. The largest change in chloride concentration can be seen in NM7 and NM12, which historically have chloride concentrations above 900 ppm. In recent years, the chloride concentration among all wells has begun to converge to an average of around 800 ppm, similar to that of NM11.

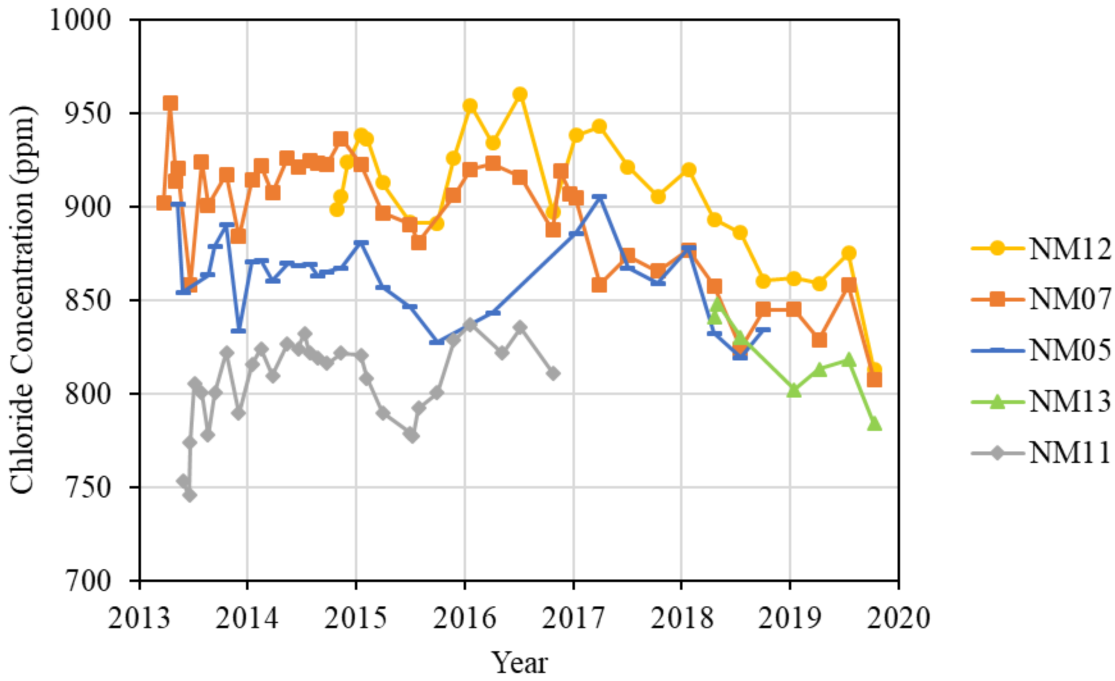


**Figure 5: Chloride concentration in production wells**

### 1.3 Reasons for Updating the Ngatamariki Reservoir Model

The main reason for updating the Ngatamariki reservoir model is to include the chloride dilution trend so that future forecasts could be further constrained. Past models have only calculated pressure and temperature throughout the reservoir. As the field has not shown any signs of decline in terms of pressure or temperature, it is difficult to develop a model that can appropriately predict future decline. The dilution of chloride is included in the reservoir model to capture the risk associated with marginal fluid entering the reservoir. If the marginal fluid entering is colder than the reservoir, the production wells could be at risk of being cooled. Modelling can help determine what the dilution trend could mean for future production enthalpies as chemistry changes are often observed prior to temperature effects. Further reasons to update the model are to include the latest production data, improve the model's match, and include the new production well NM13, which has been drilled since the last model update. Temperature and geologic information from drilling are also incorporated into this model.

## 2. TOUGH3-WELLBORE MODEL COUPLED METHOD FOR MODELLING NGATAMARIKI

### 2.1 Method Description

The method used here is an improvement from previous Ngatamariki models. TOUGH3 (Jung et al., 2017) is used for the reservoir simulator. TOUGH3 allows for significantly faster computation than TOUGH2 due to its ability to run in parallel. Faster computation allows for more complicated models. Wellbore models are run at each time step for all wells. Paiwera (developed in-house by Mercury) (Franz, 2015) is used for wellbore simulation. Paiwera is single threaded (non-parallelized) and so difficulties existed in coupling with the multi-threaded (parallelized) reservoir simulator.

For each time step, the parameters are first calculated throughout the reservoir. TOUGH3 divides the reservoir into sections and runs each section on a CPU processor. Once finished for all elements of the reservoir, the parameter values for elements that contain well feedzones are then input into the wellbore simulator. The next time step starts once the wellbore simulator is complete and flow rates for each feedzone are input into the GENER of the TOUGH3 simulation. Enthalpies are also input for any feedzone that is flowing into the reservoir. Minor changes were made to the TOUGH3 source code to synchronize the simulation and couple to the wellbore simulator.

EOS1 with two water components is used. Fresh water in shallow aquifers is water #1. Geothermal upflow rich in chloride is water #2. This allows for the chloride rich water to be traced throughout the model. Pressure, temperature, and percent of water #2 are calculated throughout the reservoir and wellbore. With the chloride concentration of the upflow, the chloride concentrations are determined throughout the model. The chloride concentration for the well is determined with the flow rates of various feedzones and chloride concentration at those feedzone depths in the reservoir model. The model is calibrated to production data.

### 2.2 Model Description

2.2.1 Mesh

The model covers a 6.3 km by 5.4 km area encompassing the P50 probable resource boundary based off magnetotelluric data and proven resource area through drilling. A rectangular mesh is used. The model is discretized into 21 columns in the x-direction and 19 columns in the y-direction. The mesh is aligned with the fault structure 45 degrees from east-west. Microseismic measurements suggest the base of the reservoir at -4.5 km elevation. The model extends from -4.5 km to the surface. Topography of the region is included with the highest point on the modelled area as 560 m elevation. The volume of the top layer of blocks vary based on the topography. The model is discretized into 34 vertical layers with finer resolution around feedzones and the Intermediate aquifer. This creates a model composed of 13,167 grid elements in space. The model has 17,153 elements for calculation due to MINC where fracture elements and matrix elements exist in the same location in space.

2.2.2 Boundary Conditions

The boundary condition on the base of the modelled volume is a hot plate. Below -4.5 km is one element that connects to all elements of the bottom layer. This hot plate element has extremely low permeability ($1x10^{-25}$ mD) and is held at 300°C. This means the hot plate element does not supply fluid, but it does supply heat to the base of the model. A mass flow of 110 kg/s at 1380 kJ/kg is supplied to the base of the modelled area (at -4.5 km) between NM7 and NM12 to represent the upflow of geothermal fluid. This upflow is 100% water #2. The top layer of grid elements of the model extending from 200 m elevation to elevation of topography is held at 5 bar and 20°C. Blocks on the boundary of the meshed volume in the reservoir and aquifers are held at a fixed pressure to allow for flow in or out of the domain as depicted as arrows in Figure 6. The horizontal red arrows depict the deep outflows (beneath the clay cap) inferred from well temperatures and MT survey data. It is assumed the chloride concentrations of the inflows to the Intermediate and Whakamaru aquifers is negligible. If a fixed pressure block provides fluid to the domain, the provided fluid is 100% water #1. The temperature of fluid provided by fixed pressure blocks is defined by a 70°C/km geothermal gradient.

2.2.3 Permeability and Flow Paths

The permeabilities used in the model create three major zones of permeable rock. The permeable hot reservoir extends from -4.5 km up to a sloping clay cap. In the southern part of the field, the top of the reservoir is at -1430 m, while in the north part of the field the clay is much shallower. The top of the reservoir is at -400 m in well NM2. The reservoir area in map view is modelled as the probable resource boundary P50. The reservoir is dual-porosity MINC with 1% fracture volume and 300 m fracture spacing in all directions. Fractures have a permeability of 100 mD in the x- and y-directions and 20 mD in the z-direction. The low permeability zone (5 mD horizontally and 1 mD vertically) found in NM8 and NM9 is included in the northern part of the field. The hot chloride-rich fluid flows up out of the reservoir through a section known as the "leak" to the Intermediate aquifer (connection A in Figure 6). Some flows along the base of the clay cap and out to the northeast, southeast, and southwest. Well interference is observed between NM7 and NM12. This is modelled by a 500 mD fault horizontally across the field connecting the two wells and 100 mD vertically from -1430 m to -1470 m elevation. The permeability is 100 mD across the fault horizontally.

The two major permeable zones overlying the hot reservoir are the Whakamaru and Intermediate aquifers. Both are widespread across the field. The Whakamaru aquifer extends from -680 m to -200 m elevation. It is modelled with a single porosity of 10% and permeability of 300 mD. Low permeability clay (0.005 mD) separates the Whakamaru aquifer from the reservoir in general. Three connections exist between the reservoir and the Whakamaru aquifer (connections B, C, and D in Figure 6). One is located near NM11 and pre-production allows dilute and cooler fluid to flow down from the Whakamaru into the reservoir (connection C). This allows for the lower chloride concentrations and lower temperatures observed in NM11. It has a vertical permeability of 20 mD and provides about 9 kg/s to the reservoir. The remaining two connections are flowing up out of the hot reservoir before production. Upon plant start up, the drawdown reverses the flow in each. The reversal of flow is what allows the chloride to remain stable for the initial few years of production before starting to dilute. One is located near NM2 (connection B) and causes the observed cooling in NM2. The other (connection D) is between NM11 and NM12 and causes dilution of chloride in the reservoir. Both connection B and D have high vertical permeability of 1 D. Some stratification within the Whakamaru aquifer exists in the model to allow for more control over the pressure in flow connections. In reality the aquifer may be more widely connected. The Whakamaru aquifer is separated from the Intermediate aquifer by low permeability clay. The Intermediate aquifer flows south to north. North of the leak warmer temperatures and higher chloride concentrations have been measured. It covers depths from -180 m to 200 m. It has 10% porosity and 500 mD horizontal permeability and 300 mD vertical permeability. The leak has a permeability of 300 mD horizontally and 30 mD vertically.

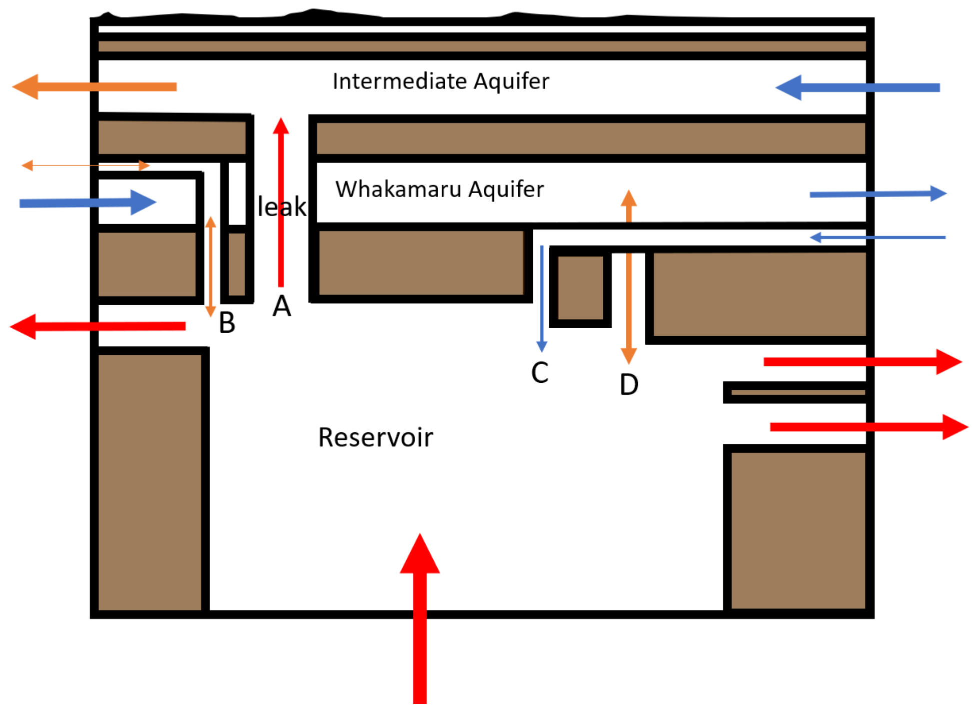


**Figure 6: Diagram of major flow paths in model viewed in cross-section with north to the left and south to the right. Note: not to scale.**

## 3. MODEL MATCH TO DATA

### 3.1 Natural State

The state of the field before production is called "natural state." The modelled pressures, temperatures, chloride concentrations, and therefore flows are stable (<0.01% change over 1,000,000 years). Figures 7-13 show the data in red and the modelled value in blue. Overall, the model provides an accurate match and is an improvement from previous models. In Figure 7 the modelled reservoir pressure is compared to the pressure at the pivot points of wells as determined with shut PTS data. The pressure match in the monitoring wells is split into the hot and cold sections of the Intermediate aquifer (Figure 8). The left plot is of the monitoring wells in the north (hot) and right plot is of the wells in the south (cold). Accurately representing the pressure difference between the deep hot reservoir and the shallow intermediate aquifer is necessary for assessing the risk of the leak turning into a downflow. The model demonstrates this pressure difference and captures this risk.

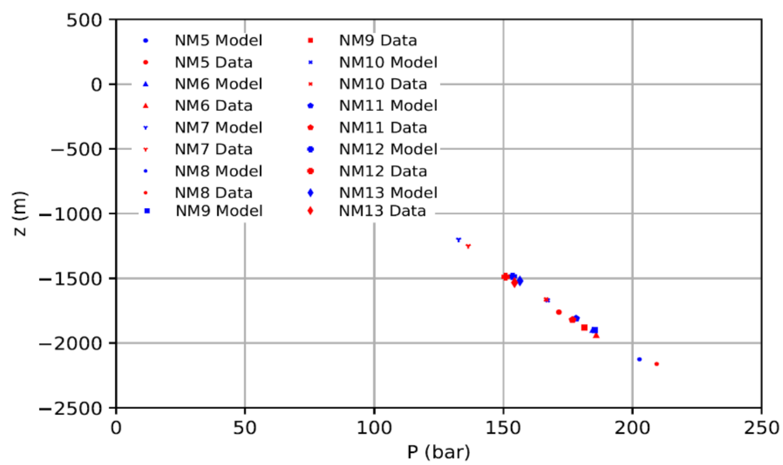


**Figure 7: Natural state pressure match in reservoir**

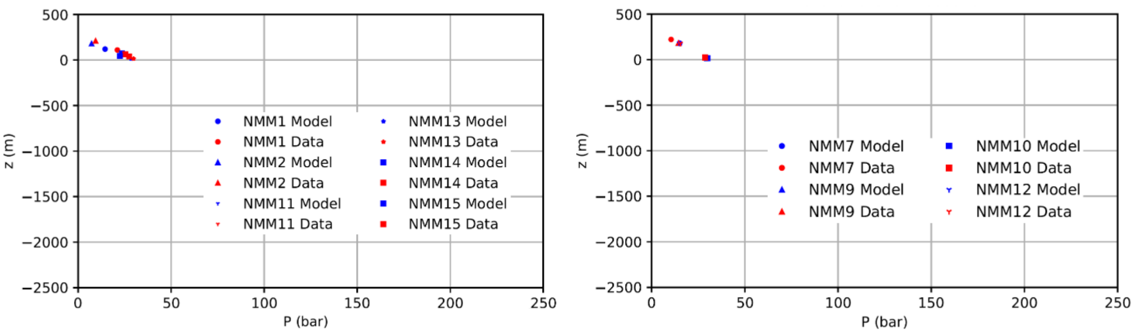


**Figure 8: Natural state pressure match in Intermediate aquifer**

The natural state temperature for each well is compared to the modelled value in Figure 9. The temperature profiles with depth are from the shut PTS with the longest heat up time after drilling and before production. The temperature profile for injection well NM6 may not have been fully heated in the reservoir. No data is available for NM8, NM9, or NM10. NM11 data is a Horner time estimate. The low temperature modelled at the base of NM11 is due to the downflowing connection from the Whakamaru aquifer in natural state. NM12 and NM13 are not included in natural state as they were drilled after production started. The reservoir temperature is slightly overestimated in NM3 in the model but in general this model creates a representative temperature gradient within the reservoir laterally and vertically. The modelled temperature in the Whakamaru aquifer is colder than measured in NM5, NM7, and NM11. This version of the model provides the best temperature matches in the Intermediate and Whakamaru aquifers to date. The previous model had temperatures that were over 50°C too hot in the Intermediate aquifer at NM1 and NM4. The inversion in NM2 and NM3 was not captured in the previous model but is now accurately represented. The previous model did not contain the Whakamaru aquifer. It is now widespread in the model as observed.

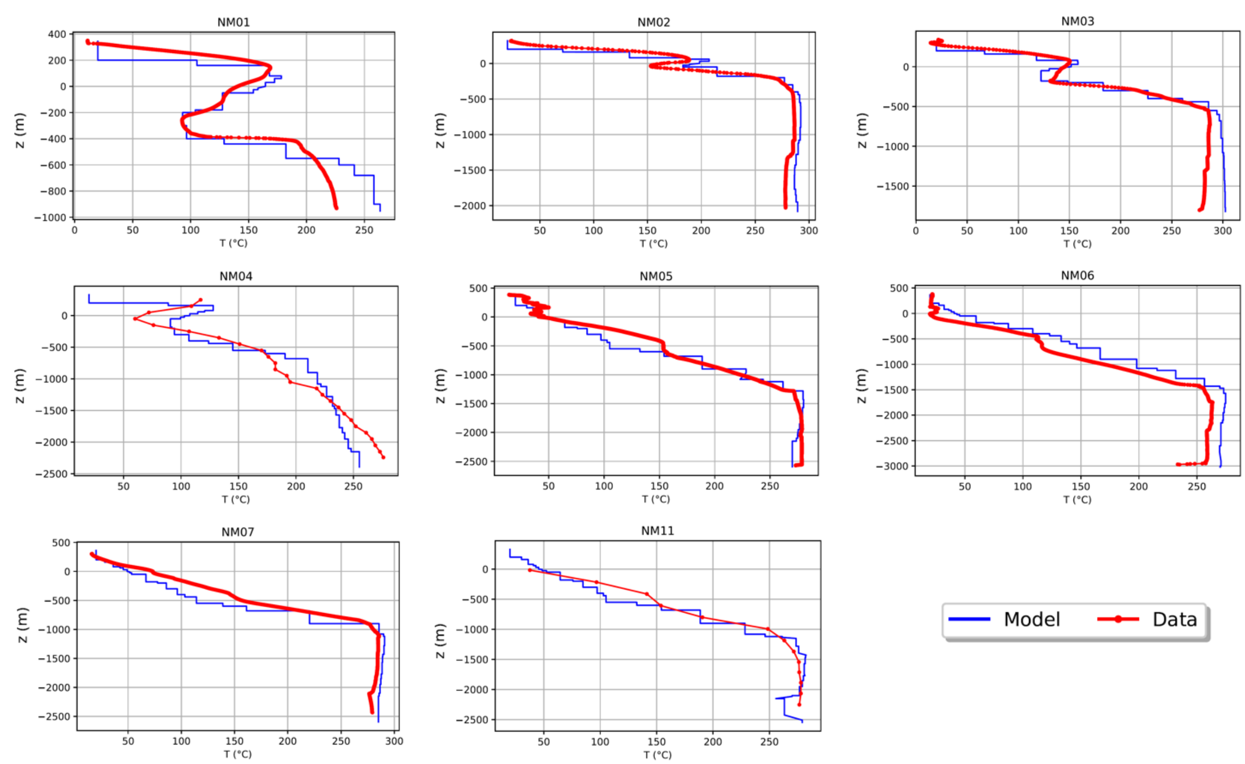


**Figure 9: Natural state well temperature match**

### 3.2 Production History

The model is calibrated though matching the production history data. The model is appropriate for future production forecasts if it can accurately recreate the past observed trends. The reservoir pressure is measured in monitoring well NM3 (Figure 10). The stable trend of the data is captured in the model with the correct magnitude. The previous model expected more variation in pressure between 2017 and 2020, dipping to -4 bar by 2020. In the production area, shut PTS are used to determine the pressure at production wells (Figure 11), with the model appropriately matching the measured pressure. The last two data points in NM11 are when NM11 is no longer producing.

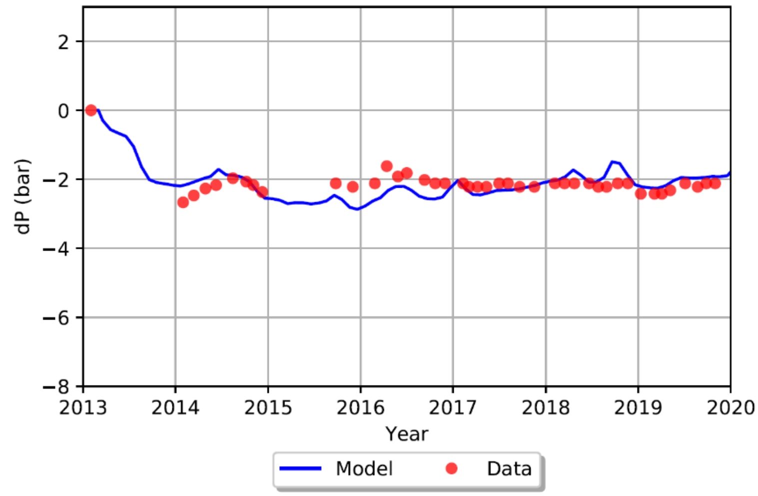


**Figure 10: Model match to reservoir pressure**

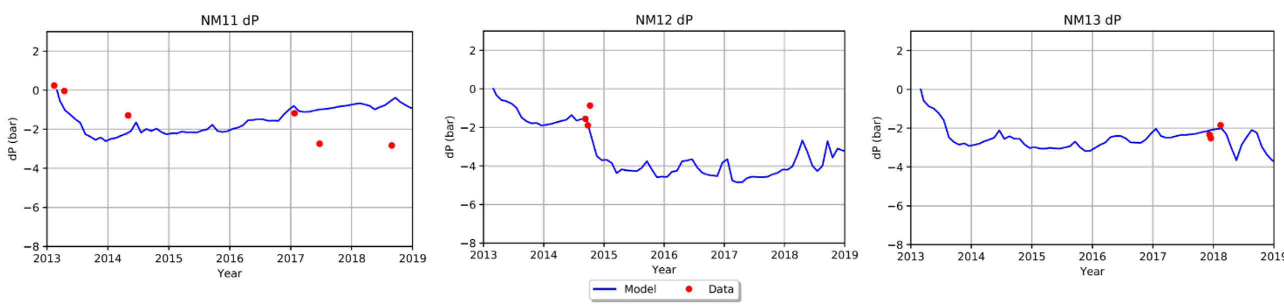


**Figure 11: Model match to pressure in production area**

The model match to plant enthalpy is shown in Figure 12. It recreates the observed trend of slightly increasing and then stable enthalpy. The updated model presented here provides a more accurate match to plant enthalpy than the previous model. The previous model predicted a lower plant enthalpy in the last few years than has been observed. This model matches the magnitude within 5 kJ/kg during the last few years when only the current production wells are used. The match to individual production wells enthalpy is shown in Figure 13. Initial data points show lower enthalpies due to residual cold drilling fluid. Today, only NM7, NM12, and NM13 are used by the plant. These are most important to match for forecasting future production, and the model match is best in these wells.

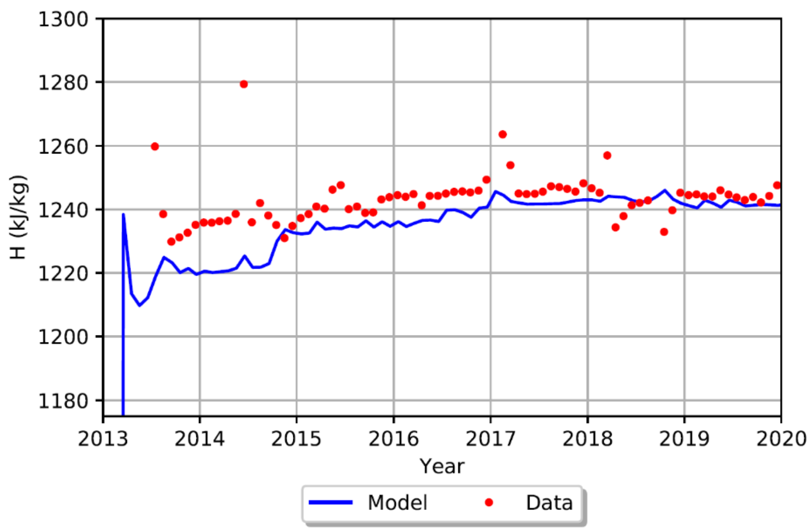


**Figure 12: Model match to plant enthalpy**

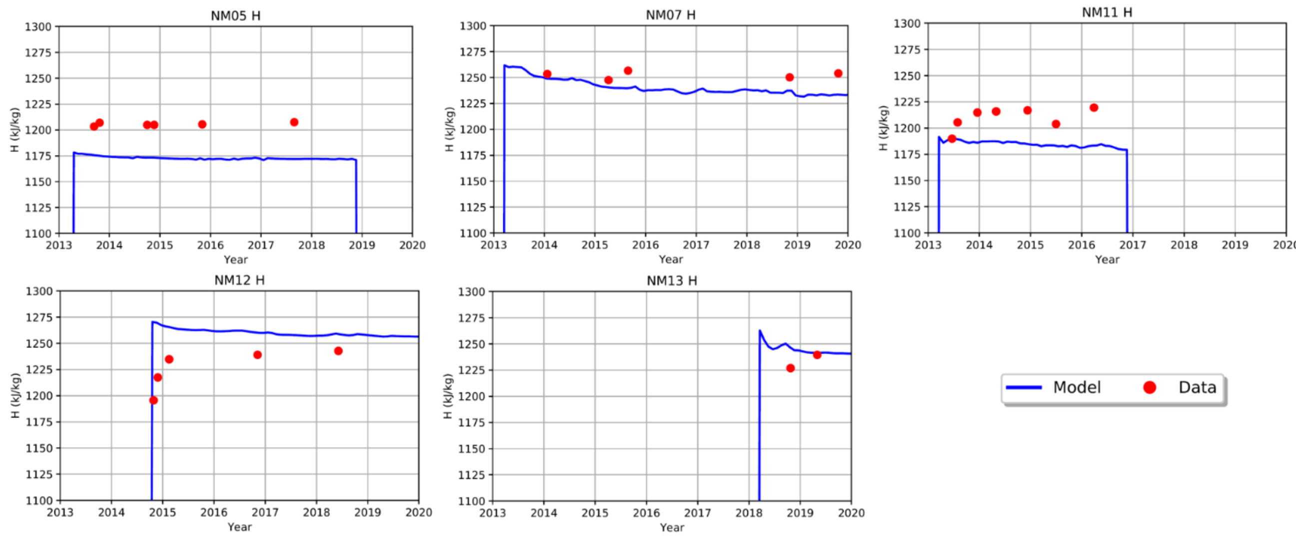


**Figure 13: Model match to production well enthalpy**

The model match for chloride concentration in shown in Figure 14. The upflow in the model has a concentration of chloride of 1000 ppm, as inferred from historical data. The initial distribution in chloride concentration is recreated throughout the reservoir, with NM12 and NM7 having the highest concentrations as observed. The modelled magnitude matches the data in all wells. The chloride concentration dilutes over time, especially in NM11, NM12, and NM13 in the model. The model may not capture the full magnitude of the chloride concentration change in NM7, however the declining trend in chloride from 2017 is observed. The initially flat and then dilution trend in chloride concentration is achieved by a flow initially out of the reservoir that reverses direction in 2016. Initially 22 kg/s is leaving the reservoir, while in 2019 38 kg/s is entering the reservoir. No previous Ngatamariki model includes the chloride distribution and concentration changes over production time. This model provides improved forecasting because it demonstrates the past change in produced fluid with fluid recharge from non-geothermal sources while recreating the observed enthalpy and pressure trends and magnitudes.

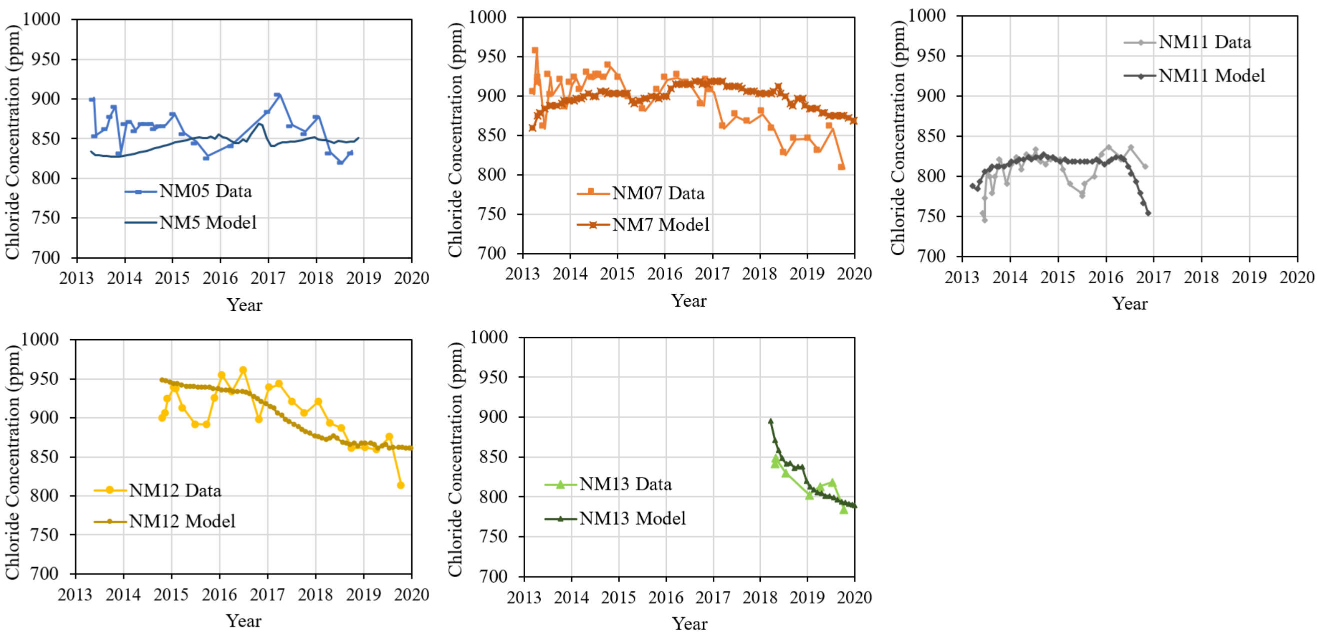


**Figure 14: Model match to chloride concentration in production wells**

## 4. UNCERTAINTIES

The Ngatamariki reservoir model presented here shows accurate pressures, temperatures, and chloride concentrations of the field over the past 7 years that no previous model has shown and therefore provides improved forecasts of future production. However, it is possible different model setups can also match the observed data as several uncertainties remain about the flow paths in the subsurface.

Pressure changes within a reservoir are to be expected during production even with a full injection scheme. The injected fluid is significantly colder that what is taken out, therefore taking up less volume. This causes a continual decrease in reservoir pressure over time. The flat pressure response observed at Ngatamariki is due to sufficient fluid recharge into the system. It is unknown exactly where this recharge comes from and what temperature it is. It could be hot recharge at depth, however as a conservative model, it is assumed here the hot recharge (upflow) does not change over time. The recharge could be cold but far from production wells and hence no temperature effects would be seen. It is modelled here as cold recharge close to production, and therefore it is possible the model is too pessimistic. The model also allows less fluid to leave the reservoir through the deep outflows and the leak. A version of the model without deep outflows from the reservoir was attempted. All recharge was either through the leak or connections to the Whakamaru aquifer. The version of the model could accurately recreate the enthalpy trend, however matching the reservoir pressure response and dilution at production wells simultaneously was unsuccessful. The model presented in here accurately shows the pressure response of the reservoir by having sufficient marginal recharge entering the reservoir. Different modelled marginal fluid flow paths could be further tested for future model versions.

A distribution in chloride concentration was observed at Ngatamariki prior plant start-up. This implies some wells are fed more from geothermal fluid and some have more fresh water from elsewhere. The fresh water could be coming into the reservoir through a variety of pathways. For the sake of making a pessimistic model, it is assumed the dilute fluid comes directly from the cooler overlying aquifer. The temperature match in the Whakamaru aquifer being slightly cooler than observed, high permeability in the connection, and high fracture spacing further provides a pessimistic scenario. The Whakamaru aquifer is used as a source of chloride-dilute fluid rather than the Intermediate aquifer because it is closer to the reservoir. The pressure in natural state in the Intermediate aquifer compared to the reservoir is such that is unlikely the flow direction of the leak reversed. The pressure within the Whakamaru aquifer is unknown as all wells that intersect it are cased in that section. The current model setup makes it difficult to demonstrate the leak reversing direction in extreme scenarios of future production. In extreme drawdown scenarios, recharge comes into the reservoir from the Whakamaru instead of the Intermediate aquifer through existing downflowing connections.

It is possible the dilute fluid that existed in the reservoir during natural state near NM11 was separated from other production wells during the first few years of production. The area could have stimulated which then allowed dilute fluid to reach the other production wells in recent years. This is not the modelled method because it requires changing the permeabilities through production time. Permeability changes due to scale formation are not included in the model. If dilution is present in natural state, a well will initially show low chloride that increases in concentration over the first few years of production. Therefore, an additional dilute flow into reservoir other than the natural state dilute flow in is needed to recreate the trend observed in the data.

## 5. CONCLUSION

The Ngatamariki reservoir model is improved to include a tracer for chloride concentration and updated to accurately match the latest production data. Improvements to the temperature match were achieved from previous model versions. This model is run through a new method using TOUGH3 coupled with Paiwera wellbore simulator. Well feedzones are a source or sink (GENER) in the TOUGH3 simulation. It is demonstrated here EOS1 can be used as a proxy to model chloride concentration in the reservoir by using two water components. The model is able to recreate the observed decline in chloride concentration while representing the plant enthalpy trend and reservoir pressure drawdown. This is achieved with flow connections between the hot reservoir and overlying Whakamaru aquifer that reverse during production time. The wells do not observe major cooling despite cooler fluid entering the reservoir and the plant continues to produce sustainably. Including chloride concentration in the model allows for better management of the reservoir as chemistry changes are often a precursor to temperature changes. The model provides a robust tool for predicting future performance of the field for electricity generation.

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