AN UPDATED COMPUTER MODEL OF THE ROTORUA GEOTHERMAL FIELD

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Keywords: *Computer modelling, Rotorua*

ABSTRACT

Two improvements have recently been made to the model of the Rotorua Geothermal Field, developed at the University of Auckland. First, a finer, regular rectangular model grid is used. Secondly, a Leapfrog-based geological model and an alteration model are used to better define the permeability structure of the computer model.

With a new regular rectangular grid, we can run the model with AUTOUGH2 or Waiwera, and with the Waiwera version we are able to use iWaiwera for rapid parameter estimation (inverse modelling).

With this computer model, based on a better geoscientific conceptual model, we have obtained a good match to the large suite of downhole temperatures and to the pressure histories measured in a small number of wells.1.

Introduction

The Rotorua geothermal field, located in the Taupo Volcanic zone in New Zealand, is of both cultural and economic significance to New Zealand. It is regarded as taonga (treasure) by the Maori community and it is an important tourist destination. The Rotorua geothermal field (RGF) is of great scientific interest as it has one of the most impressive collection of geothermal surface features, including geysers, in the world. It is unusual because it has a large number of varied surface features, many individual direct-use users of the resource but no geothermal power production. Sustainability of this geothermal resource is an important issue and one about which numerical modelling can provide insight.

1.1 Rotorua geothermal field

The Rotorua Geothermal field is located under the township of Rotorua in the North Island of New Zealand (Figure 1). The traditional use of springs at RGF by Māori for bathing and cooking has a very long history and received international

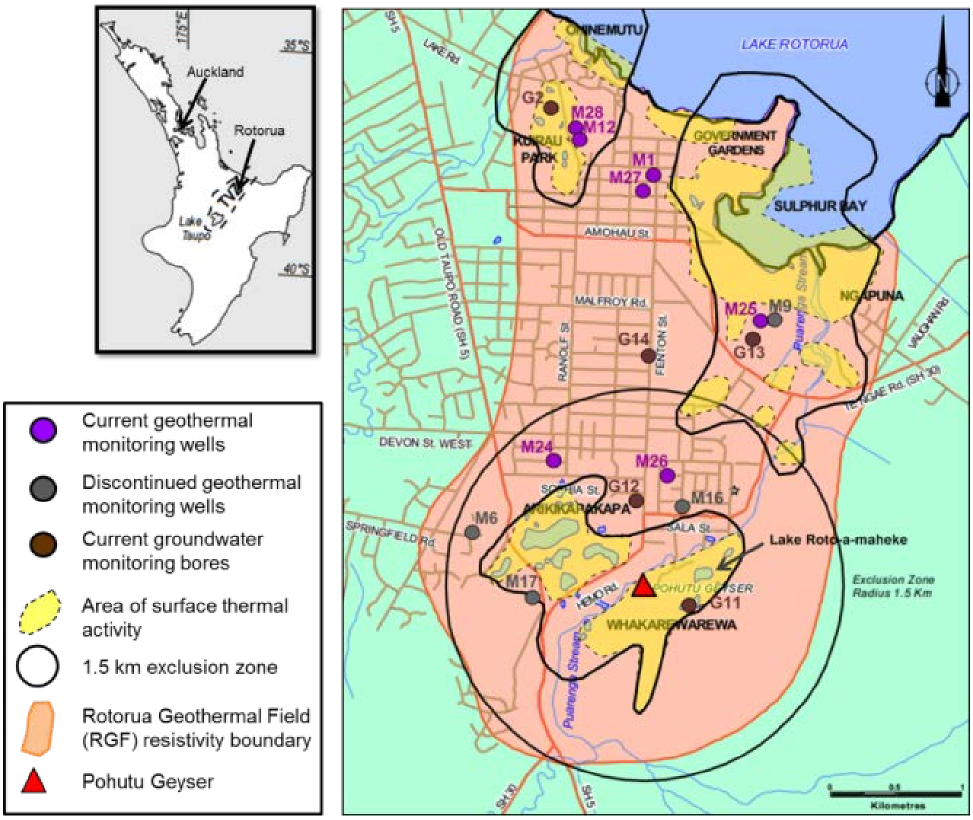


Figure 1: A map of the Rotorua geothermal field showing the surface manifestations, the exclusion zone, the location of the monitoring wells and the extent of the reservoir. Reproduced with permission from Ratouis et al. 2016.

Proceedings 42nd New Zealand Geothermal Workshop
24-26 November 2020
Waitangi, New Zealand
ISSN 2703-4275

attention when it was reported on by European settlers in the 1800's.

An intensive drilling campaign, with over 900 wells drilled between the 1950s and 1980s, led to a significant decline in pressure and a decline in surface activity (Grant et al., 1985). This led to the establishment of the Rotorua Geothermal Monitoring Programme (RGMP) by central government in 1982 and resulted in the Bore Closure Programme which came into effect in 1986 (O'Shaughnessy, 2000). Following a recommendation from the RGMP, a 1.5km radius production exclusion zone was created around Pohutu geyser (as shown in Figure 1) with the intent of restoring the significant surface features that were in decline. Since then Environment Bay of Plenty (EBOP) has assumed responsibility for managing the resource (1991) with the key objectives of monitoring the recovery of geothermal features and protecting surface features while providing allocation of the resources for present and future use (EBOP, 1999).

1.2 Numerical modelling

Computer modelling of geothermal fields is an important tool for predicting the future behaviour of the reservoir (O'Sullivan et al. 2001; O'Sullivan and O'Sullivan, 2016). The idea of modelling is to set up a model that describes the heat and mass transfer in the underground reservoir based the subsurface rock structure. The characteristics of this flow are determined by model parameters, such as permeability and the hot upflow. During the modelling process best-estimates of these parameters are obtained through calibration to measured data such as downhole temperature profiles, transient pressure data and transient enthalpy data. Once a reasonable match between the data and the model is obtained and the model gives a good representation of the conceptual model of the field, it can be used to make predictions about the future state of the field.

The Geothermal Modelling Group at the University of Auckland has worked on many iterations of a numerical model of the RGF over several years (Febrianto et al., 2013; Ratouis et al. 2014, Setiadi et al., 2014; Ratouis et al. 2015abc, Ratouis et al. 2016abc, Ratouis et al. 2017). This paper discusses the latest improvements to the model. First, a new grid has been set up that uses a regular rectangular grid in order to be compatible with the Waiwera geothermal simulator (Croucher et al., 2020). Secondly, an updated geological model that more accurately represents the stratigraphy and fault structures is used to map the geology on to the numerical model. Thirdly, an alteration model (or clay cap) is included and which allows more flexibility when calibrating the near-surface permeability structure. The model structure is discussed in more detail in Section 2; in Section 3 the natural state and production history modelling results are shown and discussed.

2. MODEL IMPROVEMENTS

2.1 Regular rectangular grid

In this latest version of the model we switch to using a regular rectangular grid. This has two main benefits: first it is compatible with the Waiwera geothermal simulator (Waiwera cannot handle the five-sided blocks used in the 2-into-1 mesh refinement used in our previous model) and secondly fault structures are represented more realistically near the boundaries of the model.

Waiwera is a parallelised geothermal simulator that has been under development at the University of Auckland over the last 5 years. All previous iterations of the Rotorua model used the geothermal simulator AUTOUGH2 (Yeh et al., 2012) which is a serial code. As a result, the computational time for the model has been vastly improved (run-times reduced from hours to minutes) by moving it to Waiwera. This has several benefits, including much faster calibration and the ability to use a more refined grid that better captures structures. Also, the inverse modelling code, iWaiwera, can be used for fast automatic calibration and uncertainty quantification (Bjarkason et al., 2019; Gonzalez-Gutierrez et al., 2018).

In the new model the minimum grid size (100m x 100m) is the same as the previous model (Ratouis et al. 2016). A comparison between the old grid (48,041 blocks) and the new grid (94,701 blocks) is shown in Figure 2. The new grid also has a refined layer structure between 280-320 masl as Waiwera required full layers and we wish to match the topography and location of the water table accurately. The new grid has 45 layers, while the old grid had 30 layers. Both models extend to a base at an elevation of -1500 masl.

2.2 Leapfrog-based geological model

In previous iterations of our numerical models, the geological structure was approximate and was implemented manually. For the new model we use Leapfrog geothermal to impose a 3D geological model on to the grid, including accurately mapped fault structures. The transfer of the geological model on to the numerical model grid is done automatically and so fault dip and the layer structure of the geological units is captured accurately. The Leapfrog geological model was produced by GNS (Alcaraz, 2014).

An overlapping representation of the Leapfrog geological model and the numerical grid is shown in Figure 3.

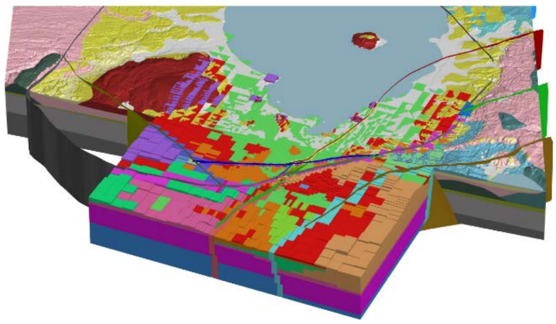
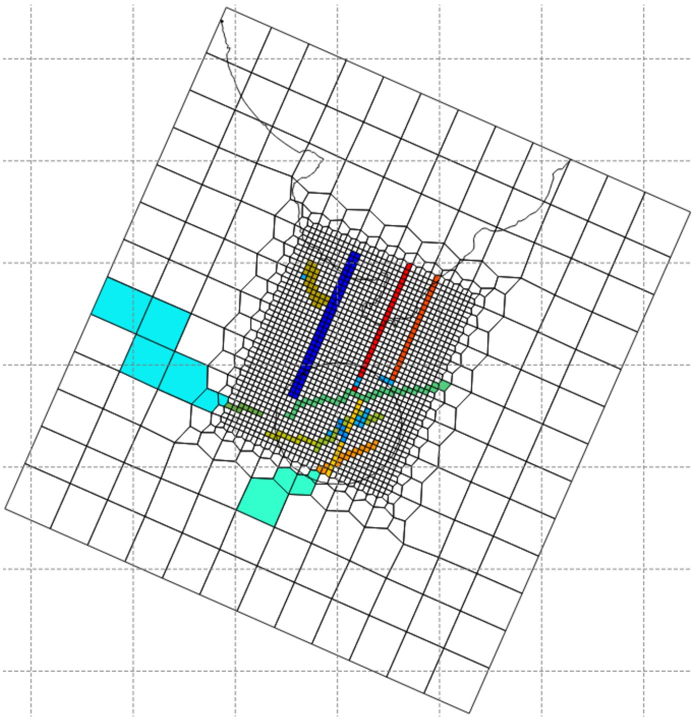


Figure 2: The Rotorua Geothermal Field, showing the numerical grid and the 3D geological model (Alcaraz, 2014).

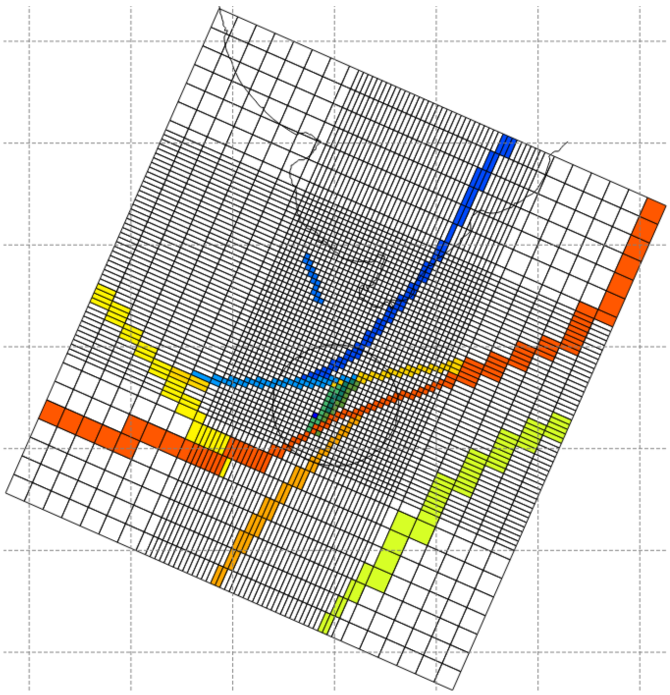
2.3 Hydrothermal alteration model

As a result of past sub-surface hydrothermal activity in the Rotorua Geothermal Field a clay cap has formed. This clay cap was not implemented in the old model but has been included in the new model. The clay cap starts to show up at an elevation of -700 masl and stretches all the way up to the surface, at around 300 masl. Figure 4 shows the extent of the clay cap in the numerical model at an elevation of 160 masl. The clay cap covers a large area of the exclusion zone and extends all the way to the shore of the lake. It was expected that the clay cap should have a low horizontal and vertical permeability, however, calibration of the natural state indicates that the horizontal permeability is of the same order of magnitude as the surrounding geological formations.

Proceedings 42nd New Zealand Geothermal Workshop
24-26 November 2020
Waitangi, New Zealand
ISSN 2703-4275



(a)



(b)

Figure 3: Comparison of the grid used in (a) Ratouis et al. 2016 and (b) the updated numerical model. Both grids include the faults found in the geological model. The exclusion zone and the shoreline of the lake are shown for reference.

Proceedings 42nd New Zealand Geothermal Workshop
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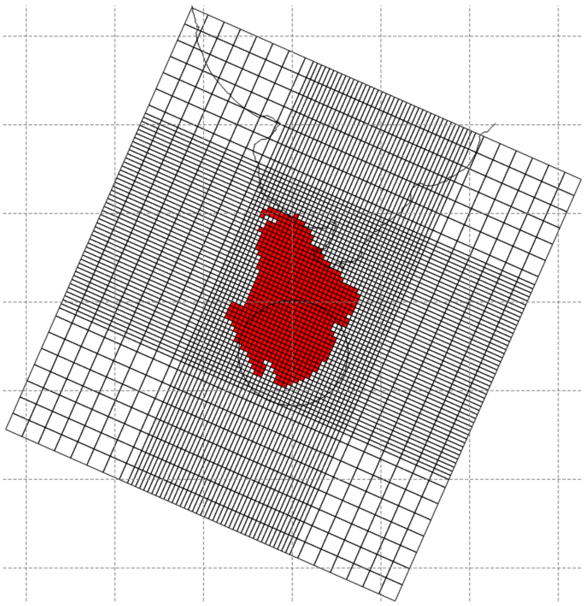

Figure 4: The clay cap, indicated in red, at an elevation of 160 masl. The exclusion zone and the shoreline of the lake are shown for reference.

2.4 Field data: model and simulator independent database

The field data include many temperature profiles, a few transient pressure and temperature histories, and CO_2 outflows. The temperature profiles are used in the calibration of the natural state and the pressure versus time data are used for calibrating the production history model. The surface flow of CO_2 (Werner and Cardellini, 2005) is used as soft calibration data, i.e., it is used as a qualitative check on the model.

There are many domestic wells and a few commercial wells in the RGF, for which the production and reinjection data have not been logged in detail. Therefore, these data are not very reliable, which makes it difficult to develop an accurate model for the production history. Consequently, it is important to quantify the uncertainty of the model parameters and results, and the future scenarios. Uncertainty quantification will be the next step once both natural state and production state are calibrated.

The data collected are in variety formats and for modelling purposes it has been converted to the JSON format. The advantage of using a database in the JSON format is that the data can be made grid and simulator independent. Thus, the same data can be accessed both by the old AUTOUGH2 model and the new Waiwera model. This framework means scripts are transferable between different models but also between models of different geothermal fields.

The data structure is set up as a dictionary containing names and values, which improves the ease of data handling.

3. RESULTS

The main goal of geothermal modelling is to make predictions of future behaviour of the reservoir. These predictions help in policy making concerning the management of the geothermal field, particularly to meet the aim of sustainable utilization. In order to make accurate predictions, a model must be well-calibrated, i.e., giving a good match to the observed field data.

In the past most calibration was done manually, but it is now common to follow manual calibration with automatic calibration based on inverse modelling software like iTOUGH2, PEST or iWaiwera. (Finsterle, 2007, Doherty, 2018a, Doherty 2018b, Gonzalez-Gutierrez et al. 2018). This is the approach we are using with our new model of the RGF.

3.1 Natural State

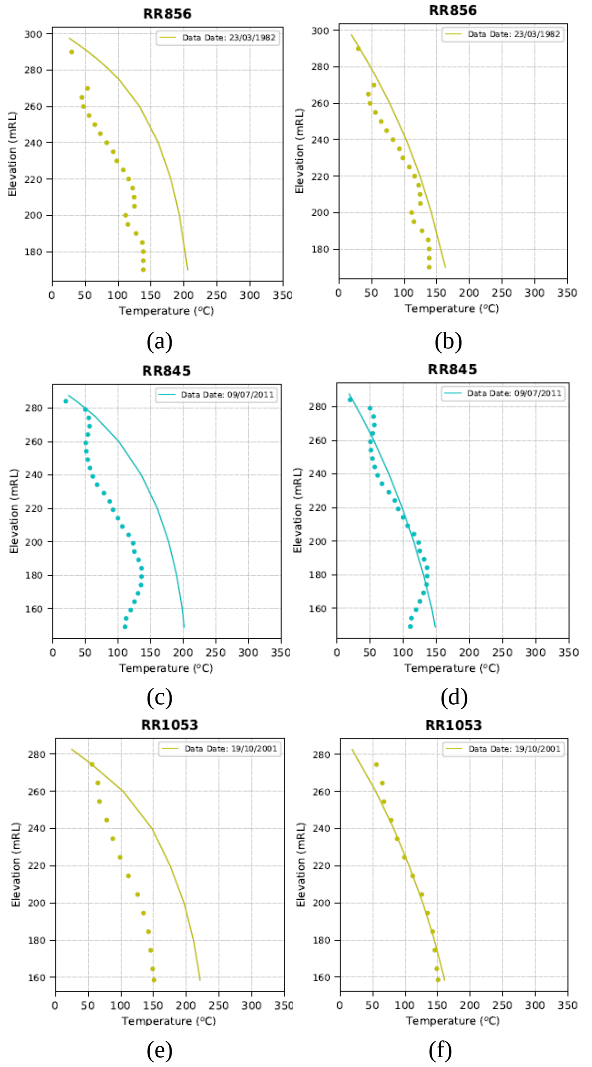

Figure 5: Downhole temperature profiles before (a, c, e) and after (b, d, f) manual calibration of the natural state. The dots are measured field data and the solid lines are model results.

For the first version of the new model, parameters were transferred from the old AUTOUGH2 model but the resulting natural state results were not very good (see Figure 5) and the updated model of the Rotorua Geothermal Field was manually calibrated to better match downhole temperature profiles by adjusting the hot upflow, permeabilities and altering the boundaries between rock types in some locations.

The results shown in Figure 5, for three wells located at different parts of the field, illustrate the improvement achieved by manual calibration. The wells RR856, RR845 and RR1053 are at Arikikipakapa, Devon Street and Government Gardens, respectively.

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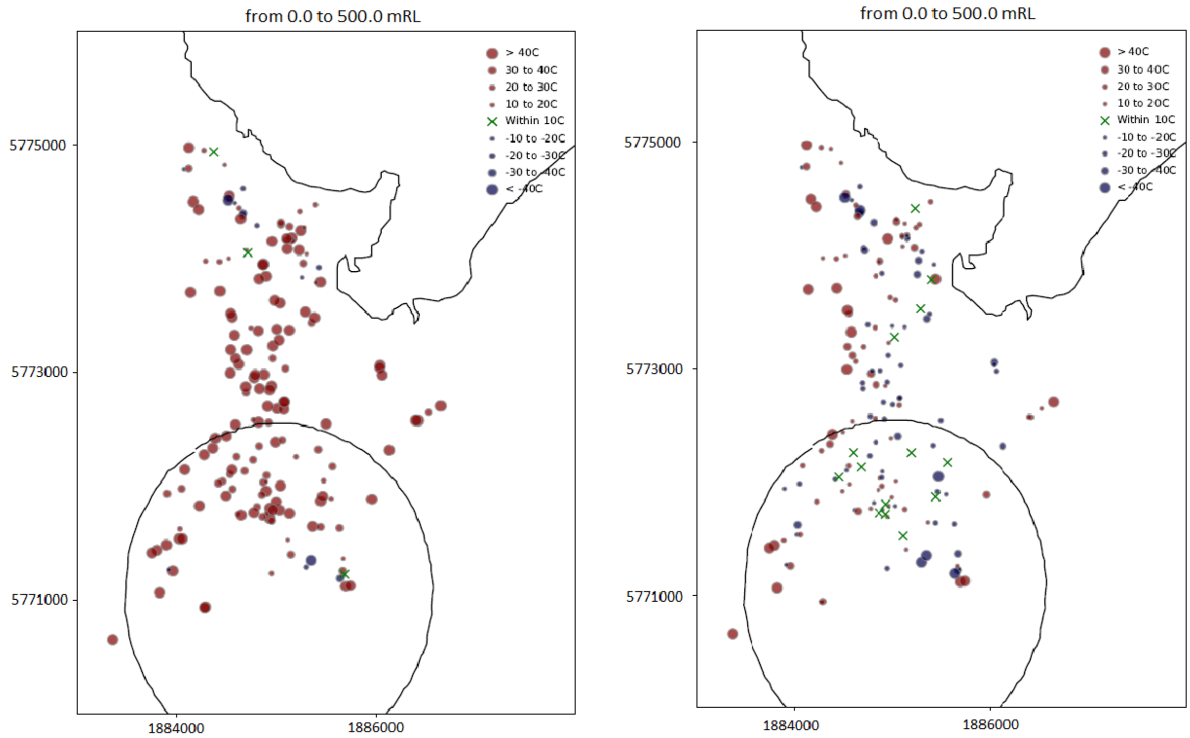


Figure 6: A comparison of the RMSD temperature analysis map before (left) and after (right) manual calibration of the natural state. The legend shows the deviation of the model compared to field data. A green cross represents a good match between model results and field data.

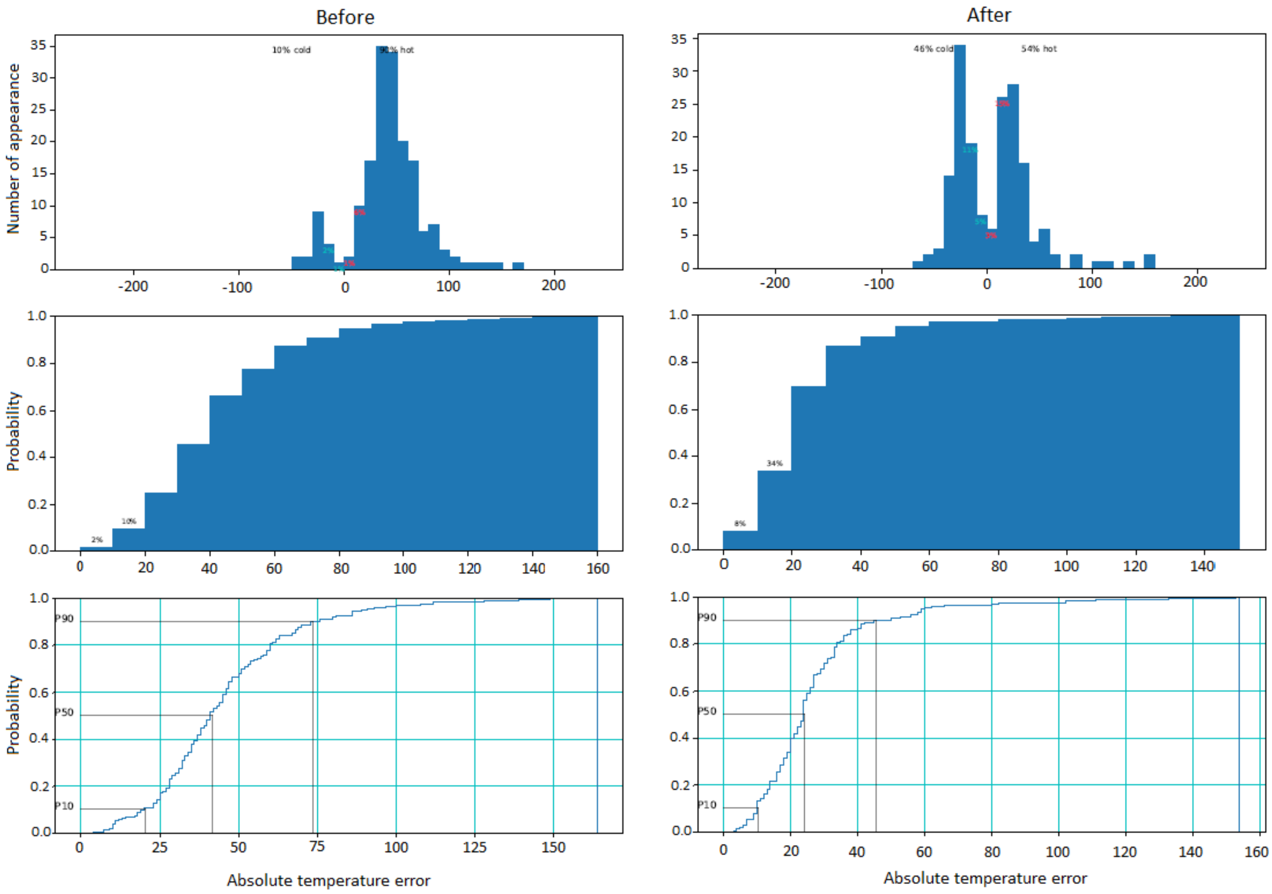


Figure 7: RMSD temperature error statistics before (left) and after (right) manual calibration of the natural state.

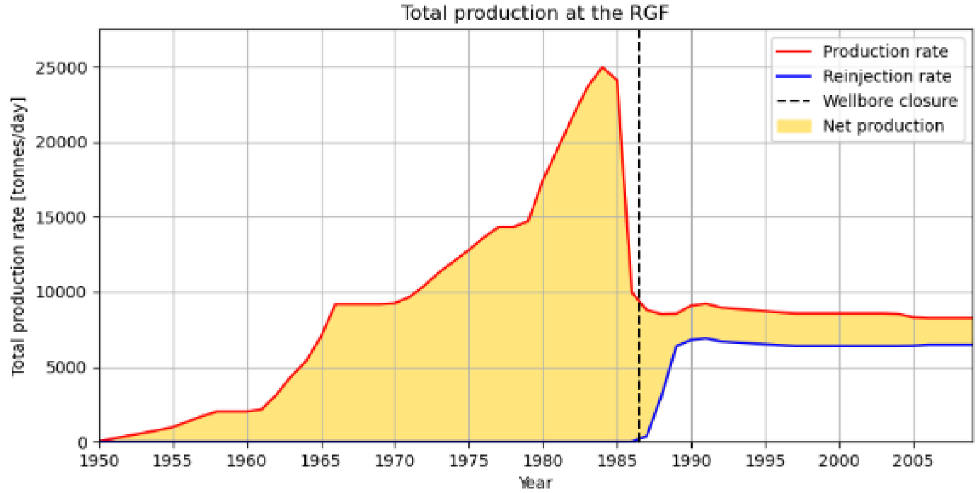
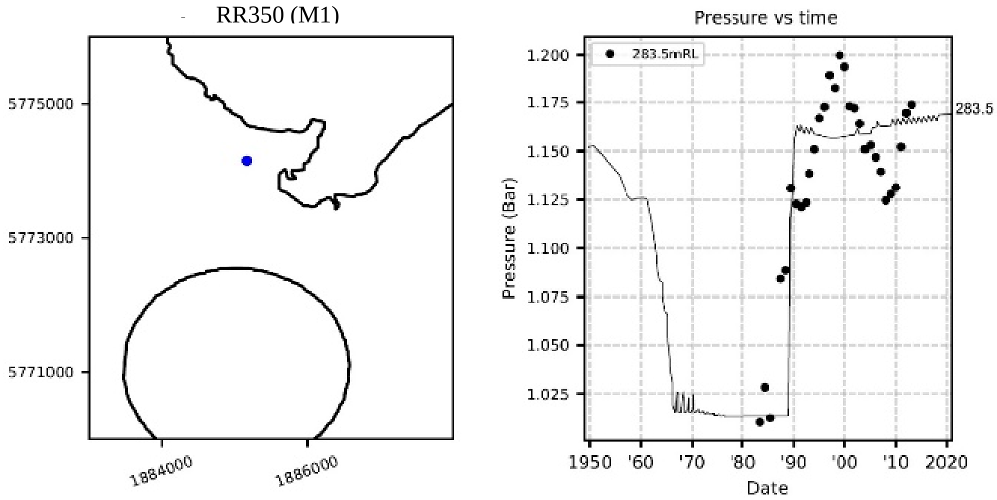
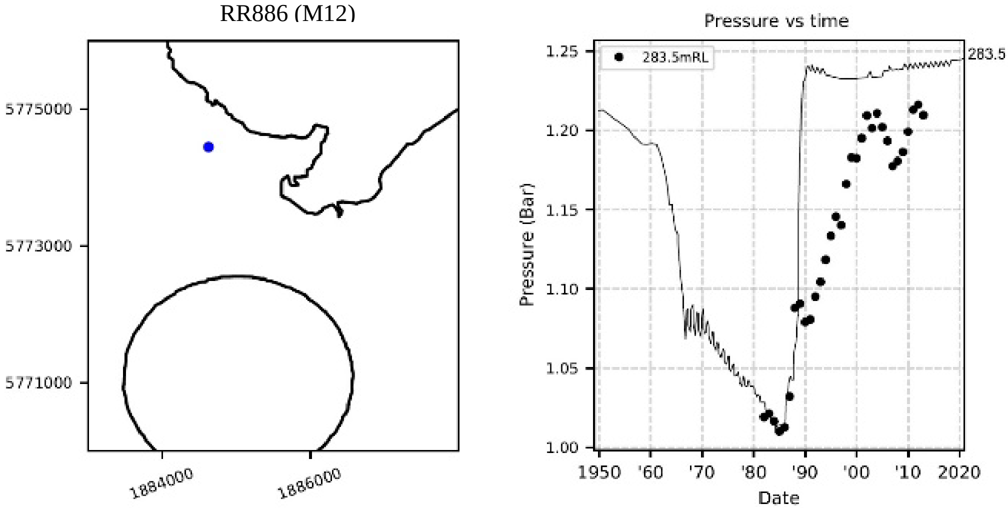


Figure 8: RGF annual average production history.



(a)



(b)

Figure 9: The location (left) and transient pressure (right) of monitor wells RR350 (a) and RR886 (b).

Proceedings 42nd New Zealand Geothermal Workshop
24-26 November 2020
Waitangi, New Zealand
ISSN 2703-4275

Furthermore, a Root Mean Square Deviation (RMSD) error analysis was calculated for the natural state temperature results. In Figure 6 an error map is shown of all the wells in the geothermal field. Green crosses represent a good match between field data and model results. An indication that the model temperature of a well is too hot or too cold is made by a red or blue dot, respectively. The bigger the dot the bigger the temperature error. From results of the error map of the initial model and the manually calibrated model it can be concluded that a considerable improvement has been made.

The next step will be to use automatic calibration software to create an even better fit between the model and the field data. In addition to the results from the error map, error statistics are used to confirm the improvement of the natural state model. In Figure 7 we compare the temperature error statistics of the initial and manual best-fit natural state model. The top histogram shows that before manual calibration most wells were too hot (Figure 7a), whereas after manual calibration about half of the wells are too cold and the other half are too hot; nevertheless, the errors are reduced (Figure 7b). The middle histogram and the bottom graph show a considerable improvement of the manually calibrated model, namely the magnitude of the temperature error of 90% of the wells is now below 45.8 °C, where it was below 73.8 °C before calibration.

3.2 Production History

After calibration of the natural state, the next step is to calibrate the production history model. Data on the production history, available from 1950 to 2020, is used as an input for the simulation. Figure 8 represents the yearly-averaged production and reinjection rates. The data contain mass flow rates and enthalpy of production and reinjection. Downhole temperature profiles, transient temperature, transient pressure and CO_2 outflows data are used to calibrate the production history model. If necessary, the natural state model may be recalibrated after the calibration of the production history model.

The transient pressure is measured in a few monitor wells. Figure 9 shows results for two of these monitor wells, M1 and M12. Both wells show a reasonable match between model results and field data. Further manual and automatic calibration will be executed to improve the production history model.

4. CONCLUSIONS AND FUTURE WORK

The updated computer model of the RGF gives a better representation of the actual reservoir because of the implementation of a more accurate geological model. Furthermore, the new numerical grid gives the opportunity for faster simulations and automatic calibration using Waiwera and iWaiwera, respectively. The manually calibrated natural state model shows a good match with the field data.

The next step will be automatic calibration of the natural state model to create the best possible match with field data. This will be followed by manual and automatic calibration of the production history model. Once the model is well calibrated it can be used for forecasting macro-scale effects on the state of the reservoir under different production/injection regimes. It can also be used to assist consent applications through investigating the effect of individual users on the system.

There is always an uncertainty in the field data, especially for the production history data, due to the lack of detailed logging of the many personal wells. Therefore, a computer model of the RGF requires extra attention for uncertainty quantification of model parameters and future scenarios. Consequently, this will be the focus of future work.

ACKNOWLEDGEMENTS

We would like to acknowledge the help of Susana Guzman and Angus Yeh from the Geothermal Institute of The University of Auckland.

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