AN UPDATE ON NUMERICAL MODELLING OF THE WAIRAKEI-TAUHARA GEOTHERMAL SYSTEM

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ABSTRACT

A longstanding collaboration between Contact Energy Ltd (CEL) and University of Auckland has resulted in the development of a series of numerical models of the Wairakei-Tauhara geothermal system. Maintenance and improvement of these models enables them to be used as tools for reservoir management and project planning. This work describes the modifications and improvements that have been made to the Wairakei-Tauhara model over the period 2010 – 2014.

The model used for the modelling study that formed part of the documentation supporting CEL's successful application for resource consents for the Tauhara 2 project contained 9011 blocks and was developed in 2008-2009. Since then the 9011 model has been refined and the latest model now contains 41458 blocks. This refinement was particularly targeted at improving the accuracy of the model in representing the shallow zone of the system.

1. INTRODUCTION

Wairakei-Tauhara geothermal system is located in the centre of North Island, New Zealand. A large part of it lies under the Taupo township.

There is a long history of modelling studies of the Wairakei geothermal system. Early modelling attempts started in the late 1950s were restricted by the available computer technology and were all based on a lumped-parameter approach. In 1970s, various geothermal reservoir simulators were developed, and Wairakei was frequently used as test case because of the availability of data. A paper by O'Sullivan *et al*. (2009) provides a summary of the past history of modelling of Wairakei geothermal field. The Wairakei model has gradually increased in both complexity and size. This paper describes the most recent advances.

1.1 Simulator and tools

The model described here is developed using a family of reservoir simulators based on TOUGH2 (Pruess *et al.*, 1999). TOUGH2 is a well-established finite volume code for simulating complex multi-phase multi-component fluid flows in porous medium. It is widely used for geothermal reservoir modelling. TOUGH2-MP and AUTOUGH2 are the codes used to run the current model. TOUGH2-MP (Zhang *et al.*, 2008) is a parallelised version of TOUGH2 and is useful to speed-up the simulation by using multiple CPUs. AUTOUGH2 is a locally customised version of TOUGH2 which includes more equations of state, more solver options, and various well-types that are useful for future scenario modelling (Yeh *et al.*, 2012).

As the size and complexity of the model has grown it has become difficult to manually construct and modify the model. Various software tools and utilities have been developed and used for the construction, calibration, and management of the models. Many of these are based on PyTOUGH (Croucher, 2011). A couple of GUIs such as Mulgraph (Bullivant *et al.*, 1995) and TIM (Yeh *et al.*, 2013) are also used to visualise the model inputs and outputs.

1.2 Model calibration

Calibrating the Wairakei-Tauhara model is an iterative process. For each set of parameters both natural state and production history simulations are carried out and the results are checked against field data. Then the parameters are updated for the next iteration of calibration.

The natural state model represents the geothermal system in its pre-exploitation state. This is simulated by running the reservoir model until a steady state is achieved, for each set of model parameters. Model results are then compared to measured down-hole temperatures. For wells that were drilled early on it is reasonable to assume that their temperature profiles are unchanged from the pre-production state. For wells drilled at later stages their measured profiles are also compared with model results taken from the appropriate time in a production history simulation.

The steady state reservoir conditions from the natural state model are then used as initial conditions for the production history model. The production model has the historical production and injection mass flows specified at the model blocks in which the feed zones are located. The field data used for matching includes changes in temperature, pressure, production enthalpy, size of steam zones, and surface flows.

Recently the model has been used to run future scenarios as part of CEL's planning for projects such as the Te Mihi Power Station (Hudson *et al.*, 2012) and the Tauhara II project (O'Sullivan and Yeh, 2010).

2. MODEL STRUCTURE

2.1 Grid structure

Model 2014 consists of 1002 columns, each divided into 56 layers, whereas Model 2009 (O'Sullivan and Yeh, 2010; Yeh *et al.*, 2010) has 324 columns and 34 layers. Figure 1 and Figure 2 show plan views of the block structures for the two models. The layer structures are compared side by side in Figure 3.

In addition to having a finer grid than Model 2009, the Model 2014 has a more uniform block structure, thus avoiding having a very large block connected to a much smaller one (which is computationally undesirable).

Both models use the EOS4 equation of state for mixtures of air and water so that the shallow unsaturated zone can be explicitly included in the model.

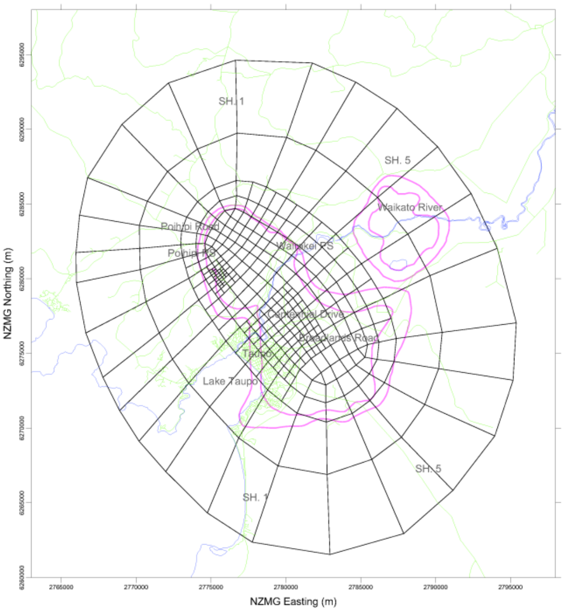

Figure 1: Location and orientation of Model 2009 (9011 blocks, 324 per layer)

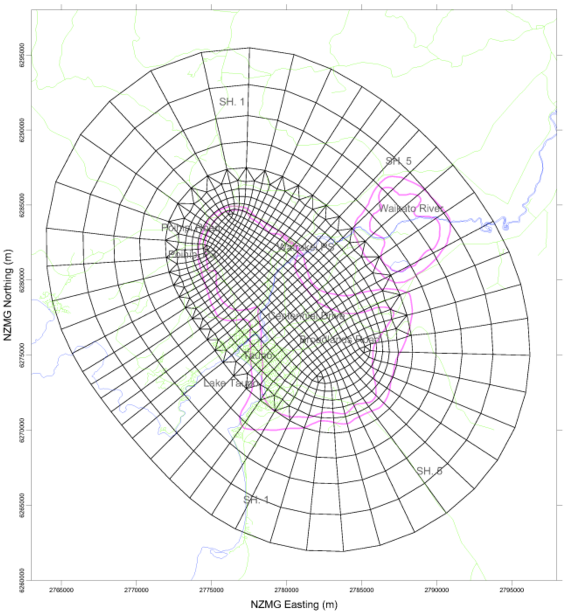

Figure 2: Location and orientation of Model 2014 (41458 blocks, 1002 per layer)

Triangular columns are used to join the smaller blocks in the centre of the model to the larger blocks in the outside recharge region. The shape of the triangular columns has been optimised in order to reduce the skewness, which in turn reduces the numerical errors associated with the model mesh. The optimisation process also tries to make the connections perpendicular to column faces (Croucher and O'Sullivan, 2013).

The finer part of the mesh is designed to cover the main areas of interest in the Wairakei-Tauhara borefields. As for Model 2009 and previous models, the grid for Model 2014 is rotated by approximately 45 degrees from North so that the columns align with the common fault trend occurring throughout the Wairakei-Tauhara area.

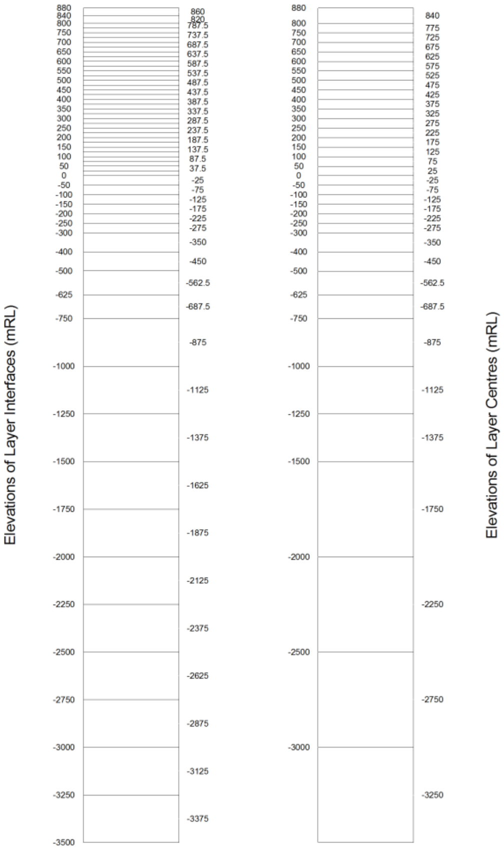

Figure 3: Vertical structure of Model 2014 (left) and Model 2009 (right)

The top of the model follows the topography and so some blocks are removed from the top few layers in the low-lying areas. One benefit of the refined grid used for Model 2014 is that it allows the top surface of the model to more closely match the topography.

As shown in Figure 3 the vertical layer structure has also been refined. Above sea level, Model 2014 has a layer thickness of 25 metres – half the thickness of the 50 metre layers used in Model 2009. This change was made to improve the representation of the shallow geology and hydrology of Tauhara in the model. Similarly, the deepest part of the model has been refined, with the layer thickness of 500 metres used in the 2009 model reduced to 250 metres. This change was made to allow the model to more accurately simulate some of the deep feed zones in recently drilled wells.

2.2 Boundary conditions

Constant atmospheric conditions are applied over most of the top surface of the model, i.e. pressure of 1 bar and temperature of 15°C. Air and water are allowed to flow in and out of the model and unsaturated zones occur at higher elevations.

A constant rainfall of 1000mm/year is assumed for the natural state model, with an infiltration rate of 7.5% represented by the injection of cold water (at 10°C) into the top of each column in the model. For the production history simulations, Model 2014 additionally includes the historic annual rainfall, whereas Model 2009 maintained a constant rate. Historic annual rainfall data was obtained from the National Institute of Water and Atmospheric Research (NIWA, 2012) from 1953 (the start of the production history simulation) to the present day.

Some columns lying under water bodies, such as Lake Taupo and the Waikato River, have a different top boundary condition. The "atmospheric" blocks of these columns use a colder constant temperature of 10°C and a hydrostatic pressure corresponding to the temperature and depth of the lake and river. Here fluid is also allowed to flow into and out of the model. Note that at these lake and river boundary blocks there is no injection of rainfall.

In the Model 2009 there were only 6 columns under Lake Taupo with the "wet atmosphere" top boundary conditions. With the refined Model 2014 there are now 50 columns connected to wet atmosphere blocks, located either underneath Lake Taupo or below the Waikato River heading downstream through to the Aratiatia Dam. Lake Rotokawa is also represented by a wet atmosphere block.

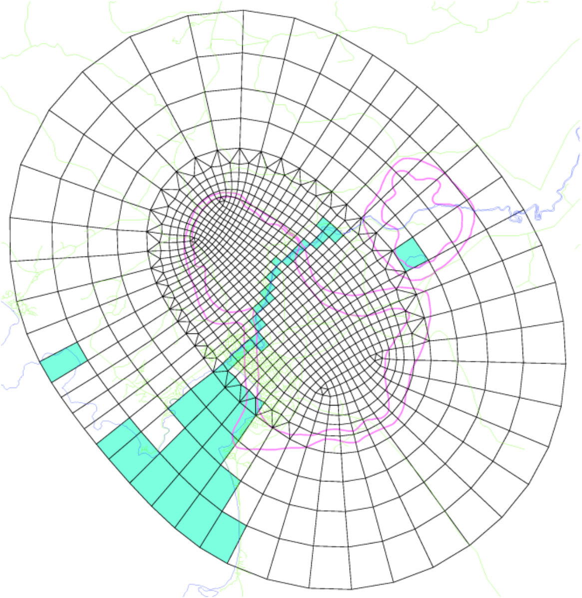

Figure 4: Location of the wet atmosphere blocks for Lake Taupo, parts of the Waikato River and Lake Rotokawa in Model 2014

The side boundary of the model is closed to flows of both heat and mass in the natural state. However for production history or future scenario simulations, flows are allowed to go into or out of the side boundary. This allows recharge into the model in the case of pressure draw-down from production and avoids spurious pressure build-up in the case of injection near the edge of the model.

At the bottom boundary there is injection of both heat and mass into the model (see Table 1). The background heat flow is represented by the injection of heat at a low rate at the outer edge and a higher rate close to the hot part of the system. High enthalpy water is injected at the base of selected column to represent the deep hot up-flow (see Table 2) from the part of the large-scale convective system that is too deep to be included in the model.

In the production history and future scenario simulations, there is additional pressure controlled mass up-flow. This hot recharge is only included at blocks where there is an up-flow of hot water and is only induced if the pressure of the basement layer drops below the natural state level.

Table 1: Heat and mass flow at the base of Model 2014

	Wairakei	Tauhara	Rotokawa	Total
Conductive heat (MW)	30.19	39.41	0.64	70.24
Mass (kg/s)	379.85	126.41	81.00	587.26
Convective heat (MW)	436.83	187.11	137.70	761.64
Total heat (MW)	467.02	226.52	138.34	876.88

Table 2: Deep hot inflows

Location	Enthalpy (kJ/kg)	Temperature (°C)
Wairakei	1150	263.3
Tauhara	1350, 1500, 1600	301.0, 325.9, 340.6
Rotokawa	1700	353.3

3. OTHER MODEL IMPROVEMENTS

3.1 Deep permeability and upflows

In recent years, many new wells have been drilled, some to a depth of two-kilometres or more. Some were drilled at locations where previously there was little or no data. The data from these wells were included in the construction and updating of the Leapfrog-based three-dimensional geological model of Wairakei-Tauhara (Alcaraz *et al*, 2010).

The three-dimensional structure from the geological model was interpolated on to the grid for Model 2014 and provided a check on the rock-type assignment in the reservoir model. The locations of faults and the geological units are used as guides when adjusting the permeability during model calibration. The improvement of the lateral and vertical resolution of the grid enabled the model to capture more of the finer details of the geological structure.

Other geophysical information from magnetotelluric and micro-seismic surveys has also been integrated into the three-dimensional geological model (Sepulveda *et al.*, 2012). Thus the three-dimensional geological model provides a very useful tool for systematically feeding knowledge from various fields of geoscientific expertise into reservoir model. Model 2014 has benefited greatly from this development, especially in deciding on the structure of the deep part of the reservoir, where traditional data obtained from drilling is sparse or non-existent.

The distribution of the deep hot upflow has been modified during the calibration process. The pattern of blocks where high up-flow rates are specified is now more closely aligned with the high permeability zones at depth, based on the three-dimensional structure of the faults from the geological model.

Figure 5 shows the up-flow flux at the base of Model 2014. The deep up-flows are more structured than in previous models, which had a comparatively uniform up-flow over the whole of the Wairakei area. Overall the total mass flow at Wairakei remains approximately the same as for Model 2009, but the total mass flow at Tauhara is slightly larger.

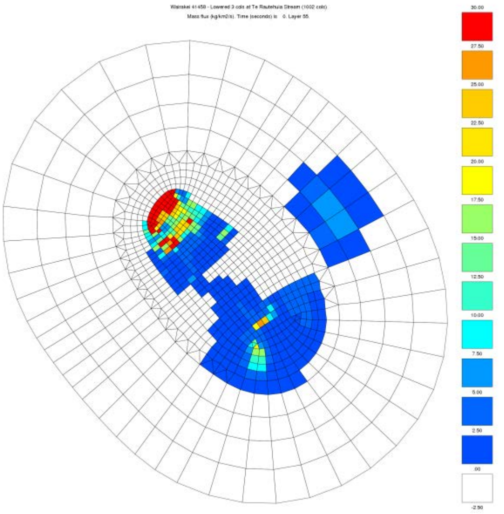

Figure 5: Up-flow at the base of Model 2014 (modified to align more with the deep permeability structure dominated by faults mostly running north-east to south-west).

3.2 Surface thermal features

Two different methods are used to represent surface thermal features in the model. The first method uses a "spring well" in the model to allow reservoir fluid from depth to ascend directly to the surface without mixing with the cooler fluid in the surface blocks. This approach is required when the column in the model containing the hot spring is of a much larger area than the cross-section of the actual flow path of hot fluid. The second method is to have model blocks with high vertical permeability, allowing the fluid to flow through all the blocks in the column before reaching the surface. This requires the grid to be fine enough to resemble the actual flow path through a series of connecting blocks.

Model 2014 has much smaller grid blocks in most areas, allowing the representation of more of the thermal features with a column of high permeability blocks instead of spring wells. The high permeability column approach however also enables the possibility of cold surface water flowing down to reservoir level under certain conditions. We have undertaken experiments with the current model using both methods to find out which provides the best match to the field data.

During the calibration, it was also discovered that certain thermal features implemented using the second method (a column of blocks with high permeability) are sensitive to the surface elevation of the columns and sometimes it is not obvious how to choose the correct elevation. This is because the top elevation of each column was computed by smoothing the topography data. Thus small stream valleys that are relatively deep relative compared to their width cannot be accurately represented. The smoothing process caused the surface elevation of the column to be much higher than the floor of the stream valley, which is often where the thermal features are located. In the model their behaviour is partly controlled by the elevation of the valley floor. Hence for a small number of columns the surface elevation was adjusted to match the elevation of the thermal features.

3.3 Improvement in matching field data

The temperature and pressure data from recently drilled wells has provided new data for improving model calibration.

In Karapiti, Otupu and nearby Northern Tauhara areas along the Waikato River, new injection wells provided data in an area previously unexplored. Figure 6 and 7 are two of such examples. This area is in the middle of the permeable path between Wairakei and Tauhara that provides the strong pressure linkage between the two areas. It is important to accurately model the planned injection in this area as it may affect the pressure at both Wairakei and Tauhara significantly. Therefore additional data to help calibrate the model in this area is very useful.

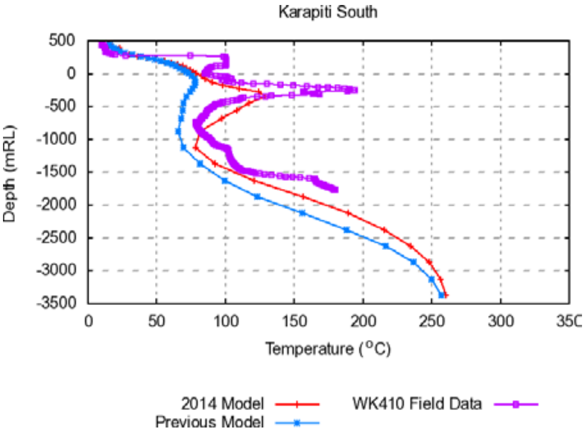

Figure 6: Temperature profile of the new well WK410 drilled near Karapiti.

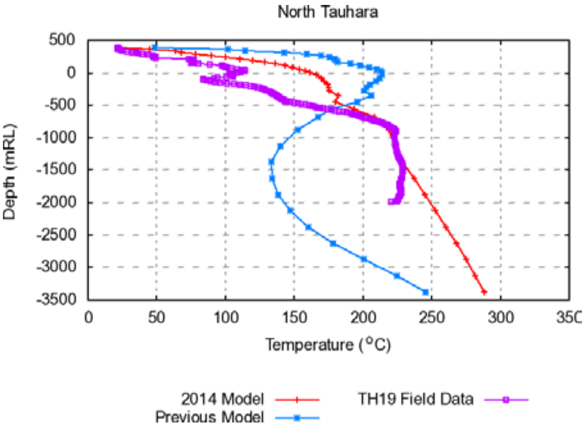

Figure 7: Temperature profile of the new well TH19 drilled near Northern Tauhara.

Some of the new wells at Te Mihi reach depths that are deeper than previous wells in the same area. Data from these wells has helped to improve the deep zone of the model near Te Mihi which in turn makes it more accurate for simulating future production from the Wairakei, Te Mihi and Poihipi power stations.

New wells were also drilled in Tauhara near the subsidence bowls to gather information about the mechanisms contributing to subsidence (Bromley *et al*., 2013; Pender *et al*., 2013)). They provide detailed geological information in the shallow zone because they are fully cored to well bottom (Rosenberg *et al.,* 2009). Some of these wells also provide pressure measurement in the shallow zone, which was not available before. Work is ongoing to improve the match of the model results to the data in this area.

4. MODELLING FUTURE SCENARIOS

Scenarios were run earlier with Model 2009 (e.g. O'Sullivan and Yeh, 2010) and have been run with Model 2014 for future production and injection at both Wairakei and Tauhara. The scenarios were used to test out the effects of production and injection associated with the Te Mihi Power Station project (Yeh and O'Sullivan, 2012) and the proposed Tauhara II project (Yeh and O'Sullivan, 2013).

4.1 Management of future scenario simulations

During the early stages of working out the future scenarios to be modelled, specifications are drafted by reservoir and power plant engineers. These specifications are usually general descriptions of the scenarios, which need to be translated into corresponding model input files.

The main task in setting up a TOUGH2 input file for a future scenario simulation is the assembly of the generators (sinks and sources) that represent the production and injection wells. In the simulations future production is provided by existing wells together with a set of make-up wells that are put into production when needed, and then removed when they become unproductive or are no longer needed. For a particular group of wells a target total mass flow or total steam flow is assigned. Similarly, make-up injection wells can be added in when necessary to dispose of the separated geothermal water and steam condensate. The total mass to be injected depends on the total production at any given time.

In the case of future scenarios for Wairakei-Tauhara the model contains a number of zones that operate independently (for example, Wairakei, Tauhara Stage I, Tauhara Stage II, Poihipi and Rotokawa), each with a set of make-up wells. Each zone operates with different parameters, such as separator pressure, injection pump pressure, condensate proportions, and amount of surface discharge. Additionally, each zone has its own time-varying schedule for production and injection, either as part of the operational strategy or to comply with resource consent conditions.

The assembly of the production and injection well schedules for all the zones is not straight-forward, partly because of the input file format and the available generator types in the current TOUGH2/AUTOUGH2 simulator.

A simulation has to be broken down into a chain of sequential model runs, each with its own correct set of generators (wells) for the time interval. Manually constructing, running these model files and extracting results is a difficult, tedious and error-prone process. This is exacerbated by the fact that the whole process needs to be repeated several times as the model is revised and changes are made to the scenario specifications.

To simplify and automate this process we have developed some scripting tools. Separate "scenario description files" are prepared and fed into scripts (using the PyTOUGH library) which generate the actual model files, run the simulations and extract the results from several output files. A description file contains simple instructions that are easy to read and modify. It also has a logical layout closer to the way scenario specifications are originally written.

A description file has the following content:

(i) Basic scenario parameters such as the start and end dates.
(ii) A list of zone names. A zone represents a group of wells that are operated together, but independently from other zones.
(iii) Within the section for each zone there is a timetable of varying well configurations.
(iv) The description of the well configuration can be as simple as one line (e.g. a target flowrate) or may require further modularised building blocks.
(v) Each building block can be (a) pointer to external file, (b) command to call other scripts that compose generators, or (c) plain lines of TOUGH2/ AUTOUGH2 generators.
(vi) Comments can be used anywhere to enhance readability.

The use of scenario description files allows us to manage complex scenarios more efficiently. For example, changing the schedule for an existing scenario is as easy as altering dates in a couple of lines in the description file. Similarly, modification of priorities among a group of injection wells can be achieved simply by rearranging the order of a few lines in the description file (each pointing to a building block description of a subgroup of injection wells).

This process has made simulation of several variations of complex scenarios quite straightforward. More work is currently being carried out to further improve the representation of production and injection wells in AUTOUGH2 and to improve our external utilities. The objective is to reflect the operation of real-world geothermal projects more realistically and more easily in the numerical models.

4.2 Wells on deliverability

Production wells on deliverability are usually used for simulations of future scenarios. The mass flow rate is calculated by multiplying the productivity index by mobility and the difference between flowing bottom-hole pressure and the reservoir block pressure. Three options are available in AUTOUGH2 for calculating the bottom-hole pressure: (i) constant pressure, (ii) pressure dependent on enthalpy, and (iii) pressure dependent on enthalpy and flow rate.

In most of the recent future scenario simulations the wells are operated using method (ii). The underlying assumption for this method, that the behaviour of the well is not too variable, is reasonably met by most of the Wairakei wells as they generally start out with a two-phase excess enthalpy that slowly declines and they have a relatively constant mass flow rate. This assumption is not so applicable for the hotter and tighter Tauhara reservoir where the future wells may exhibit enthalpy fluctuations (due to boiling caused by pressure drop) which may cause significant changes in mass flow rate as the composition of the two phase flow changes.

It was found that long term prediction of the behaviour of a production well can be sensitive to the deliverability curves used, especially when a group of wells are close to each other with fluctuations of their flowing enthalpies. A study has been carried out to review and investigate the effects of using the three different methods (Yeh *et al.*, 2015), but more work needs to be done on determining the functional dependence of the bottom-hole pressure on enthalpy and flow rate, particularly for multi-feed wells.

At present each feed of a multi-feed wells is treated as a separate "well", which is not an entirely satisfactory procedure as it does not allow for interaction between the feed zones. We are working on methods for improving the representation of multi-feed wells (Yeh *et al.*, 2015)

5. CONCLUSION

Model 2009 of Wairakei has been refined both laterally and vertically and the latest model, Model 2014, now contains 41458 blocks.

Many aspects of the model have been improved as a result of four developments:

(i) A refined and optimised lateral and vertical grid structure.
(ii) New field data available through an intense drilling programme in recent years.
(iii) Integrated information available from three-dimensional geological and geophysical model.
(iv) Improved modelling techniques and pre-/post-processing utilities.

Model 2014 has a more detailed permeability structure in the deep zone at Wairakei and the shallow zone at Tauhara. Up-flows at the base of Wairakei have better alignment with the fault system. The top surface boundary has also been improved to match the topography more closely, particularly along the Waikato River, and a more accurate rainfall history has been included.

The refinement of the model has come at some cost as the production history simulations now take approximately four times as long to run, and the convergence of the natural state simulations up to a very large time step is much slower for Model 2014. It seems that some modification of the pre-conditioner used in the linear equation solver in AUTOUGH2 may be required to solve the slow convergence problem.

A new method has been devised to aid the construction of future scenario simulation files allowing more efficient construction of scenario models as well as the ability to handle more complex scenarios.

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