Improved Visualisation of Reservoir Simulations: Geological and Fluid Flow Modelling of the Tauranga Low-Enthalpy Geothermal System, New Zealand

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Keywords

Leapfrog Geothermal, TOUGH2, geothermal reservoir, lowtemperature, numerical model, visualisation, sustainability, renewable resources

ABSTRACT

The low-enthalpy geothermal system at Tauranga, on the north coast of the North Island of New Zealand, is widely used for hot springs, commercial pools, aquaculture and direct heating. As pressure on the system increases, the need to carefully manage its use is becoming more important. By creating a Leapfrog Geothermal geological model and incorporating it into a TOUGH2 reservoir model, a fairly detailed simulation of the system can be created. Outputs from the TOUGH2 model can then be read back into Leapfrog Geothermal, facilitating direct comparison between measured and modelled temperatures, and highlighting regions that need to be better modelled. Using a 2-layer geological model comprising sediments overlying volcanic rocks, we created a TOUGH2 model covering 130 km by 70 km and extending down to 2 km depth. Relatively low thermal conductivity of 1-1.5 W/m°C from the literature appears to give a good fit to the data, but both permeability and heat flux at depth are important parameters that our modelling shows need to be better constrained. Integrating Leapfrog Geothermal and TOUGH2 software creates a useful tool in geothermal reservoir simulation, facilitating model calibration and allowing reservoir models to be more easily disseminated to a much wider audience.

Introduction

Numerical models of high-temperature geothermal fields are routinely carried out to assess energy potential, identify upflow zones for drilling targets, and satisfy resource consent requirements (O'Sullivan et al., 2001). Numerical simulations of low-enthalpy geothermal fields are less common, but are beginning to be used both to assess a field and to determine its potential usage (Pearson, 2012). Numerical simulations using specialised software like TOUGH2 can provide a lot of information, but are often limited by a lack of good visualisation that would allow areas needing improvement to be more easily identified, and results to be disseminated to a wider audience. With the development of Leapfrog Geothermal, a relatively new geological modelling software, detailed geological models can be exported for use in reservoir models, and temperatures from reservoir models can be fed back into Leapfrog for comparison with well temperature and any other data. This allows more accurate models to be created, and for model results to be visualised and shared in a way that has never before been possible.



Figure 1. Location map of Tauranga geothermal field. The brown grid shows the model extent and dimensions. Yellow dots represent cells with well data. Black lines correspond to major faults. Inset map: Location of Tauranga within New Zealand.

Tauranga, on the north coast of the North Island of New Zealand (Figure 1), hosts a low-enthalpy geothermal field that is a significant resource for the more than 120 000 local inhabitants (Statistics New Zealand, 2012). Water temperature has been measured at between 22 and 39°C in springs, and up to 60°C in wells drilled to 800 m depth (White et al., 2009). Tauranga is a popular tourist destination and hot pools and commercial swimming pools are found throughout the area, while Highway Fisheries in Papamoa, to the southeast of Tauranga city, is a major grower of ornamental and tropical fish. The low-enthalpy geothermal system is also used for domestic heating and cooling, and greenhouses (B. White, 2009). Therefore the geothermal field plays a significant role for the area, and its long-term stability and further potential are of interest to the region's inhabitants and authorities.

As the population grows and travel and technology become more affordable, low-temperature systems like Tauranga are put under increasing pressure and the question of how much they can sustain becomes of mounting importance. However, they are generally not subject to the level of management of a high-temperature geothermal field, which in New Zealand requires detailed geophysical and geological study and numerical simulations before it can be developed for electricity. Numerical simulations of low-temperature fields are therefore difficult because there are generally limited well and exploration data, and so models are not well constrained. Despite this, it is still important that these areas are studied, and recent advances in computing make it easier for all of the information available to be collated. Here, we create a Leapfrog Geothermal geological model and import it into a TOUGH2 heat and fluid flow model to simulate the Tauranga low-enthalpy geothermal field in New Zealand. We also create numerical models of measured and modelled temperature data in Leapfrog to facilitate calibration of the reservoir simulation.

Geology

Geologic Setting

Tauranga sits on the Australian plate, close to the subduction zone with the Pacific Plate. It is bounded to the west by the Kaimai mountain range and to the northeast by the Pacific Ocean. Tauranga is situated in the Coromandel Volcanic Zone (CVZ), a north-northwest trending zone that was active between ~18 and 1.5 Ma (Adams et al., 1994; Briggs et al., 2005). During this time three ignimbrite eruptions occurred and at least 21 dacite-rhyolite domes or dome complexes were emplaced (Briggs et al., 2005). These are thought to be the source of the warm water system at Tauranga (Reyes et al., 2008). Tauranga township sits in the Tauranga Basin, a tensional graben formed about 2-3 Ma (Davis and Healy, 1993).

To the east of the Tauranga area, the volcanics have been overlain by relatively young sediments. Rhyolite domes like Mt Maunganui (252 m) remain some of the dominant landforms, but these have been overlain by sediments dated at ~6.5 ka (Davis and Healy, 1993). Tidal sediments are somewhat younger, between 3.4 and 0.7 ka (Davis and Healy, 1993). Sediments thicken seawards (Simpson and Stewart, 1987), reaching a thickness of 300 m off the coast, but disappearing to the west of our study area (White, 2005). There are major faults to the south and west, but none within our study area (Figure 1) (Briggs et al., 2005).

Leapfrog Geothermal

Leapfrog Geothermal is a 3D modelling and visualisation software package developed by ARANZ Geo (Christchurch, New Zealand), with input from GNS Science (Wairakei, New Zealand), University of Auckland (Auckland, New Zealand), and Contact Energy Ltd (Wairakei, New Zealand). It is an integrated interface that allows the development of conceptual and quantitative geological models (Alcaraz et al., 2012). It incorporates lithology, structure, faulting and well data, as well as allowing geophysical and other information to be saved within the well data information. As well as creating detailed geological models, it allows surfaces to be exported in a number of formats including x,y,z so that they can be imported into other software for further calculations like heat and fluid flow models. As data can also be imported directly from TOUGH2 (Newson et al., 2012) or as x,y,z,T (for example), TOUGH2 model outputs can then be plotted against the geological model, allowing measured well temperatures, isotherms interpreted from the well temperatures, and isotherms from the reservoir model to be compared directly. This not only makes the outputs easier for a non-modeller to understand, but allows much easier and more direct comparisons for improving the fluid flow models.

Geological Model

The geological model of Tauranga was originally created by GNS Science for a Bay of Plenty Regional Council groundwater assessment (White et al., 2009). It was created in EarthVision based on well data, surface outcrops, and geological maps (e.g. Houghton and Cuthbertson, 1989; Meilhac, 2009; Leonard et al., 2009). The model comprises a layer of sediments of several hundred metres thickness under the coast that pinches out moving



Figure 2. Geological model of Tauranga geothermal system showing sedimentary deposits (yellow) overlying volcanic rocks (brown), with five times vertical exaggeration. Red dots with black traces represent the location of wells with temperature data.

west (Figure 2). Below this are a number of different volcanic units (White et al., 2009). As there is very little data about rock properties for the different volcanic units and they generally comprise similar layers including ignimbrite, tuff, breccia and lava (White et al., 2009), we created a simple model with sediments overlying one thick layer of volcanics (Figure 2). Deep well data is not available for Tauranga, but with a better-constrained field a TOUGH2 model incorporating more detailed rock types and properties could easily be created in Leapfrog Geothermal. The top boundary of the model was taken from the GNS digital terrain map of New Zealand. This simple model was then exported for use with TOUGH2, where additional layers could be added if necessary to improve the model fit to the data.

Reservoir Model

From the geological model and a number of other constraints a heat and fluid flow model can be created that allows the extent and energy of the system to be determined, as well as the possible effects of extracting energy. We used the Petrasim interface to TOUGH2 to create a numerical model of the Tauranga geothermal system.

TOUGH2

TOUGH2 is a sophisticated program to model multiphase and multicomponent fluid flow, evolved from the MULKOM code (Pruess, 1991). It numerically simulates coupled non-isothermal heat and fluid transport through porous media based on an adaptation of Darcy's Law. Gases and liquids can be included, although in the Tauranga low-enthalpy geothermal system steam is not relevant, only water. Different equations of state (EOS) simulate different components: here we used EOS3 (water, air) to simulate flow of water through a geothermal field to the vadose zone. More details on the code can be found in Pruess (1999).

Grid

The TOUGH2 grid was created to encompass the entire Tauranga area and some distance beyond (Figure 1). It covers 70 km by 130 km and extends down to 2 km depth (Figure 3). It is orientated to the northwest to follow the geographical extension of the field and to cover the locations of warm water wells (Figure



Figure 3. Leapfrog Geothermal model showing the TOUGH2 grid (blue dots). Five times vertical exaggeration.

1). Over the warm-water area the spacing is 1 km by 1 km (Figure 3), but beyond this a coarser spacing of up to 10 km by 10 km ensures that the warm-water area of interest in the centre is not affected by the boundary conditions of the model.

The Model

The model was run with fairly simple initial conditions for two million years, to represent the age of the Tauranga Basin (Davis and Healy, 1993). Initially the interior and boundaries of the model were set at atmospheric pressure (101 kPa) and mean annual air temperature (12°C) (NIWA, 2011). The model was fully water saturated but the uppermost layer was 100% air to represent the atmosphere (Figure 4) and had a very large volume so that the atmospheric conditions were fixed. This allowed recharge into the system to be simulated at realistic rates. Infiltration in the Tauranga area has been measured at 50% (White et al., 2007), with most of that remaining in the shallow groundwater system (White et al., 2009). Therefore recharge was injected into the second layer at 129 mm/yr to simulate 10% of the mean annual rainfall (NIWA, 2011). Vertical boundaries were set as no-flow (Figure 4). As geochemistry suggests that there is minimal flow of geothermal fluids from depth (Reyes, 2008), heat was input into the base of the model at varying rates to allow an optimal fit to be found between model temperatures and measured ones.



Figure 4. TOUGH2 model with 10 times vertical scaling showing layers, geometry and boundary conditions. Numbers represent the x,y,z model dimensions in metres.

Rock properties were either taken from the literature or are typical of fractured rock. Sediment permeability was initially 5 x 10^{-13} m² and volcanic permeability 5 x 10^{-16} m², with homogeneous layers (Petch and Marshall, 1988; Harding et al., 2010). Basal heat flux was initially 88 mW/m² (Studt and Thompson, 1969; Simpson, 1987; Reyes, 2008). Thermal conductivity was initially 1.05 W/m°C in the sediments and 1.26 W/m°C in the volcanic rock (Simpson, 1987). All of these parameter were varied to match model outputs to measured temperatures. Density, specific heat capacity and porosity were set at measured or typical values (Simpson, 1987). For more information see Pearson (2012).

Calibration

The Tauranga area has been drilled extensively for groundwater studies, providing lithological and temperature information (White et al., 2009). More than 150 wells tap warm groundwater in a 500 km² area around Tauranga (Simpson, 1987). Since 1960 temperatures have been measured in almost 400 wells. We used data from 387 wells (as others did not include depth information), including 17 wells with temperature profiles with depth, giving a total of 592 measurements. The measurements were recorded at between 268 and -904 masl, from the surface to 752 m depth. Temperatures varied between 8 and 67°C, with the majority at between 10 and 40°C. In general deeper measurements were hotter (Figure 5). These well temperatures were used as the primary constraint for the TOUGH2 model. Older temperature measurements in the area are also in agreement, with temperatures generally 35-45°C at 600 m, but sometimes over 55°C (Simpson, 1987).



Figure 5. Well temperature measurements with five times vertical exaggeration. In general well temperatures increase with depth, up to 67°C at 750 m depth.



Figure 6. Comparison of well temperature data (dots) with model temperatures. Five times vertical exaggeration.



Figure 7. Comparison of isotherms from well temperature data (solid shapes) with model isotherms (lines). Dots show the original temperature data. Five times vertical exaggeration.

Results

Previous, simplified models show that a two-layer model with two zones of heat injection can approximate the well temperatures (Pearson, 2012). However, adding more accurate topography and geological contacts shows that the model needs some refinement (Figure 6, Figure 7). In particular, the model is sensitive to heat flux, thermal conductivity and permeability. The relatively low thermal conductivity (Simpson, 1987) appears to provide a good fit to the data, but the effects of both the permeability and heat flux need to be further studied to improve the model. Leapfrog

> Geothermal allows well temperatures to be compared directly with model temperatures, highlighting poorly modelled areas, and also anomalous well temperatures (Figure 6). Comparing well and model isotherms shows trends that need to be improved, making it easier to refine the conceptual and numerical models (Figure 7). Therefore this provides a useful tool when trying to create a realistic model of a geothermal system.

Future Work

The model of the Tauranga low-enthalpy system is currently being refined so that it provides an acceptable fit to the data. This will allow the extent of the Tauranga geothermal field to be better determined, as well as providing an estimate of the energy contained in the system. Having recalibrated the model, we will then simulate production scenarios. Well locations, depths and approved withdrawal amounts from the local authorities will allow us to assess current and future usage rates and their potential long-term effects. We will also model reinjection scenarios based on actual data. From this we will be able to deduce whether the system is cooling, and if currently approved rates are sustainable. We then hope to add some additional wells to see if the current system capacity can be increased for direct use.

Conclusions

It is important to simulate low-temperature geothermal systems in addition to high-temperature ones, to assess whether current usage rates are sustainable and acceptable. Combining Leapfrog Geothermal with a TOUGH2-Petrasim model allows us to create a more accurate model, more easily visualise model outputs, and compare model outputs directly with well data. This not only makes the modelling process easier, but also facilitates disseminating TOUGH2 models to a wider audience. The Tauranga low-enthalpy geothermal system provides a perfect case study as there are a large number of wells with temperature measurements, some down to several hundred metres. Although data is typically sparse in low-enthalpy systems, it is vital that they are studied to the best of our ability, to ensure that they are used realistically and can be maintained for future generations.

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