USING RESERVOIR MODELS FOR STRATEGIC DECISION-MAKING

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Keywords: *Numerical Reservoir Models, Strategic Planning.*

ABSTRACT

Reservoir models have become important and increasingly widely-used tools for the development and management of geothermal systems. In many countries both regulators and financial institutions require that some level of numerical modelling is carried out as part of a feasibility study. The geothermal modelling team at the Geothermal Institute and Department of Engineering Science at the University of Auckland (UoA) have been developing reservoir models since the 1980s and are among the world leaders in the technology. Through the taught programme for the Post-graduate Certificate in Geothermal Technology and research degrees the UoA is also responsible for training many of the world's geothermal reservoir modellers. The worked present here is a summary of the state-of-the-art in geothermal reservoir modelling and how it is used to aid strategic decision-making. Case studies from different countries are presented covering topics such as resource planning and optimisation, re-injection strategies, predicting subsidence, environmental sustainability and enhanced permeability.

1. INTRODUCTION

The team at the UoA has three core activities with regard to geothermal technology:

1. Training
2. Research and development
3. Consulting

As consultants we use reservoir models to support strategic decision-making in a number of geothermal systems around the world. The way in which reservoir models are used varies greatly depending on the types of decisions that need to be made. Six examples using reservoir modelling to support decision-making are presented in this paper. They are summarised below and then described in detail in the following sections.

The first case study is of the Wairakei-Tauhara geothermal system in New Zealand and demonstrates how reservoir modelling can be used to assist strategic decision-making with regard to the expansion of production within an existing field. The results of the simulations not only helped management plan for the expansion but were a critical part of the successful application for resource consent that was required for the project. Because of the nature of geothermal developments, many projects are developed in stages and expansions are commonplace making the information from these types of reservoir models vital in many circumstances.

In the second case study reservoir models were used to plan for the resource utilisation of the Ohaaki geothermal system, also located in New Zealand. The simulations were used by management to determine the sustainable total steam flow for the resource. The results of the studies were also used to help obtain renewal, in 2013, of the resource consent for the continued operation of the Ohaaki Geothermal Power Project.

The third case study is of the Menengai geothermal system in Kenya. This field is still in the early stages of development but a reservoir model has been used to make preliminary estimates of the resource potential and also the response of the field to different reinjection strategies. A supercritical model was developed at the UoA which was compared to results from a standard model. This study showed that by accurately reproducing supercritical conditions, the model could provide decision makers with much more accurate information about both production potential and the effects of reinjection.

The fourth case study demonstrates the use of reservoir models to predict subsidence. This is an important area of research because of its implications for both operators and regulators. The case study shows how new techniques and more accurate approaches have enabled researchers at the UoA to reproduce historical measurements of subsidence in the Wairakei system. As these techniques are developed and incorporated into large-scale reservoir models, they will be able to provide decision makers with accurate information about the subsidence that may develop as a result of geothermal production.

In the fifth case study reservoir models are used to predict the environmental sustainability of geothermal production in the context of the Rotorua geothermal system in New Zealand. The reservoir models have been calibrated to historical data so that they can be used to help guide the environmental monitoring programme set up by the regulators. They can now be used to assess the environmental impact of different future production scenarios on important natural resources.

The final case study shows how advances in reservoir modelling techniques can provide decision makers with more accurate information about well stimulation and permeability enhancement. These important phenomena are complex and poorly understood which the makes the development of reliable, new modelling tools important for the future.

1.1 Flow simulator and other tools

The models described here were 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. PyTOUGH, a Python scripting library for TOUGH2, (Croucher, 2011, 2013; Wellmann *et al.*, 2012, 2014), was also used extensively for managing the simulations in each case study. For the rock mechanics calculations, in case studies four and six, ABAQUS is used.

2. CASE STUDY ONE: WAIRAKEI EXPANSION

Wairakei-Tauhara geothermal system is located in the Taupo Volcanic Zone (TVZ) in the centre of the North Island of New Zealand. The Wairakei Power Station was the first in the world to generate electricity from a liquid-dominated reservoir when it began feeding power to the national grid of New Zealand in 1958. Contact Energy operates the Wairakei Power Station which currently has an installed capacity of 175 MW and provides 1400 GWh of electricity per annum, equal to 4.3% of New Zealand's electricity production.

In early 2010 Contact Energy applied for resource consents for the Tauhara II project, which involves expanding the development at Wairakei-Tauhara by 240 MW with the addition of a new power plant located near Mt. Tauhara. Prior to the application for resource consents the modelling team at the University of Auckland, in collaboration with Contact Energy staff, carried out an extensive modelling study of the proposed Tauhara II development (O'Sullivan and Yeh, 2010). The study was based on the 2009 model of the Wairakei-Tauhara geothermal system that had been developed at the UoA over many years. O'Sullivan (2009) provides a good summary of the past history of modelling of Wairakei geothermal field. Figure 1 shows the location and grid structure of the 2009 model.

Most aspects of the 2009 model are similar to the model that was used to support Contact Energy's application for resource consents to build the recently completed power plant at Te Mihi (O'Sullivan and Yeh, 2007).

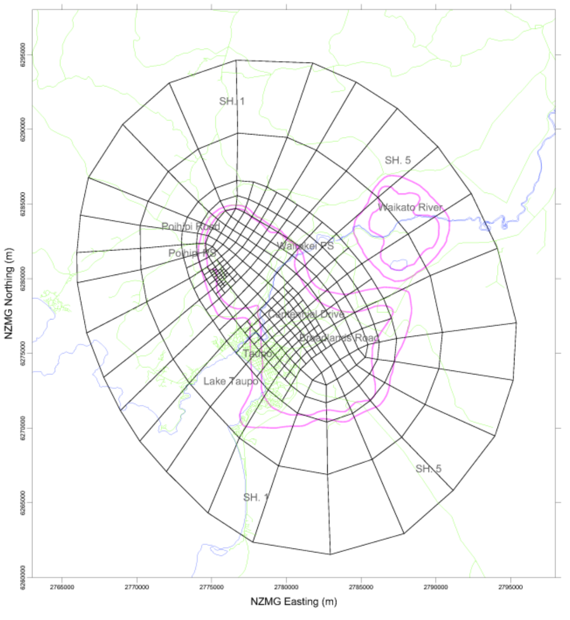

Figure 1: Location and orientation of Wairakei Model 2009/9011 (324 blocks per layer)

It accurately represented the pre-production or natural state of the system and the behaviour of the system in response to production at Wairakei. For the study of the Tauhara II development the model was used to evaluate three basic future scenarios with several sub-cases. The scenarios are summarised in Table 1.

Table 1: Wairakei Expansion Scenarios (ref)

Scenario	Description
THE	Existing environment baseline involving operation of the existing Wairakei, Tauhara I (and Rotokawa) consents out to 2060 ie assuming reconsenting as those consents expire.
THA	Tauhara II involving production from northern, eastern, southern and central zones overlaid on THE, but with Tauhara I production increased to 30,000 tonnes per day. Three sub-cases are examined as follows: (i) THA1 with no deep pressure constraint and therefore allowing a greater level of outfield injection, (ii) THA2 assuming continuation of the existing 56 bar g (57 bar a) minimum pressure at -400mRL in TH1 and TH3, (iii) THA3 with Wairakei being shut down in 2026 and both Tauhara I and II being shut down after 35 years.
THB	Tauhara II with production from northern, eastern and central zones (called scenario THB) analysed as sub-cases THB1 and THB2 as above.

The first conclusion from the scenario forecasts was that scenarios THA1, THA2, THB1 and THB2 could meet Contact Energy's target of approximately 47,300 t/day of separated steam from the proposed Tauhara II development, although with greater demands on the system and a correspondingly reduced field life for THA2, THB1 or THB2 compared with THA1.

The THB scenarios also have more limited scope for adjustment in the location of reinjection than do the THA scenarios, and therefore present fewer options for varying the reinjection strategy in order to improve field management. Figures 2 and 3 show the total steamflow produced from Wairakei and Tauhara II, respectively, supporting this conclusion.

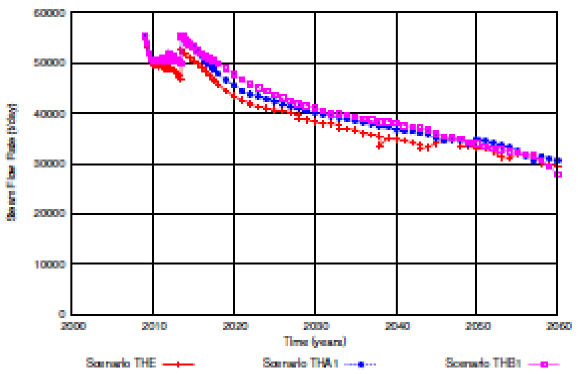

Figure 2: Steamflow from Wairakei

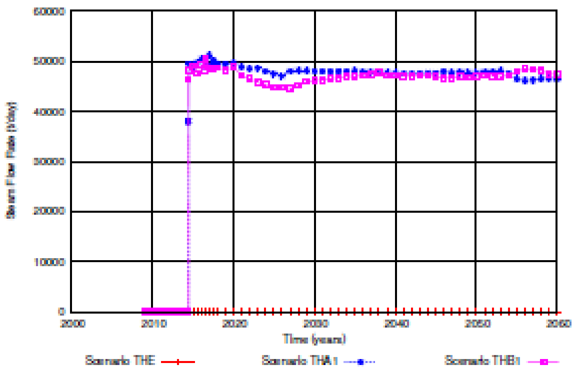

Figure 3: Steamflow from Tauhara II

The second conclusion reached was that for all scenarios Tauhara II has little effect on Wairakei and no identifiable effect on Rotokawa. This is also supported by the plots in Figure 2 and the average enthalpy plot for Rotokawa shown in Figure 4.

The third conclusion was that soon after the start of the Tauhara II project, Scenarios THE, THA2 and THB2 were close to, or achieved, the required 56bar g (57bar a) minimum pressure at Tauhara (TH1 and TH3) at the -400 mRL level. An increased level of infield injection was required to meet the target. For Scenarios THA1 and THB1 where the 57bar a target was not enforced, there is only a small extra pressure decline in TH1 and TH3 (~2bar for THA1 and ~4bar for THB1).

The fourth conclusion was that all the scenarios except for THA3 (shut-down) showed a small initial pressure drop (~1bar) at TH7 (on the northern fringe of Taupo) followed by a slow pressure increase. Near THM16 (Crown Road) there was a pressure increase of 5-7bar when Tauhara II commenced followed by a nearly constant pressure over the whole simulation period (up to 2060).

The final conclusion was that shallow pressure below the subsidence bowls at Tauhara will not decline greatly in the future and in most cases increases by a small amount.

The conclusions drawn as a result of the modelling project were a significant factor in the success of the application for resource consent for the Tauhara II project (now scheduled for construction in 2018).

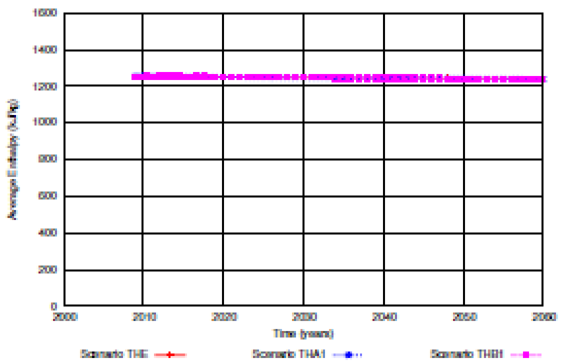

Figure 4: Average enthalpy from Rotokawa

3. CASE STUDY TWO: OHAAKI MANAGEMENT

Like other systems in the TVZ, Ohaaki is a high temperature liquid dominated convective system. However it is an unusual geothermal field in the TVZ context because of its high gas (CO_2) content.

The system has two separate upflow zones, one on each of the East and West banks of the Waikato River which intersects the field. Down-faulting of the greywacke basement creates high permeability flow paths which allow the deep hot fluid to rise and there is some connection at depth between the two zones. Temperatures in excess of 300º C have been recorded in the system. More information on the system can be found in Hedenquist (1990) and Carey *et al.* (2013).

The power plant at Ohaaki was commissioned in 1988 and had a capacity of 116MWe. During the first 5 years of production generation was maintained at ~100MWe but in 1993 the available steam began to decline. A deep drilling program was undertaken in 1995 which identified high temperatures and permeability in the deep volcanic formations underlying the West Bank (Lee and Bacon, 2000). This was relatively successful, however the steam supply continued to decline. A second deep drilling program, also focused on the West Bank was undertaken in 2005-2007 (Rae *et al*., 2007; Carey *et al*., 2013), allowing generation output to be maintained at about 60MWe. A plot of annual electricity output is shown in Figure 5.

A sequence of three-dimensional numerical models, of increasing complexity, of the Ohaaki geothermal system has been developed at the University of Auckland in collaboration with Contact Energy and its predecessors. A report on one of the most recent versions of these models (called here the 2012/22816 model) formed part of the application for the re-consenting of the Ohaaki Geothermal Power Project, approved at a resource consent hearing in 2013. A summary of the report on the 2012/22816 model and a discussion of recent improvements to the model are given by Clearwater *et al.* (2014). As well as supporting the re-consenting process, the results from the numerical models have been used by Contact Energy to optimise their production strategy at Ohaaki.

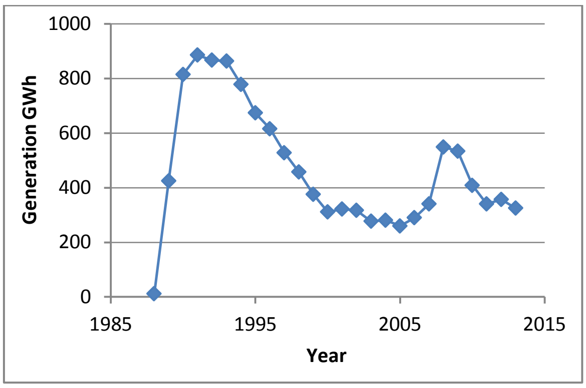

Figure 5: Annual electricity output from Ohaaki

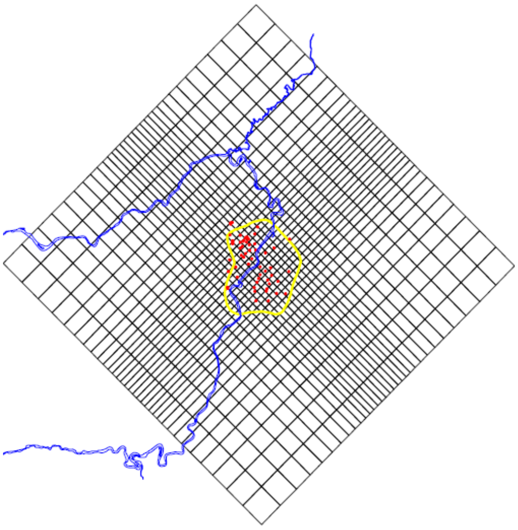

Figure 6: Plan view of the Ohaaki model grid. The blue line is the Waikato River, the yellow line the resistivity boundary, and the red dots show the wells.

Table 2: Ohaaki Future Production Scenarios (Clearwater *et al.*, 2014)

Scenario	Description
1A	Allow existing production wells to run on deliverability until 31 October 2013. A take of 35,000 t/day of mass is to then be maintained using existing wells plus make-up wells.
1B	Allow existing production wells to run on deliverability until 31 October 2013. A take of 40,000 t/day of mass is to then be maintained using existing wells plus make-up wells. This was selected by Contact as the consent application scenario.
1C	Allow existing production wells to run on deliverability until 31 October 2013. A take of 45,000 t/day of mass is to then be maintained using existing wells plus make-up wells.
1D	Allow existing production wells to run on deliverability until 31 October 2013. A take of 9,600 t/day of steam, sufficient to run one intermediate pressure turbine at full load, is to then be maintained for as long as possible using existing wells plus make-up wells. If the reservoir can no longer maintain this steam take, instead maintain a maximum take of 40,000 t/day of mass, using existing wells plus make-up wells.
1E	Allow existing production wells to run on deliverability until 31 October 2013 when all production and reinjection is ceased. This scenario is modelled in order to show the effect of the proposed consent not being granted.
1F	Allow existing production wells to run on deliverability until 31 October 2013. A take of 40,000 t/day of mass is to then be maintained using existing wells plus make-up wells. Continue until 31 October 2048 when all production and reinjection is ceased. This scenario is included to observe the effect on the system if production ceases after the 35 year consent term.

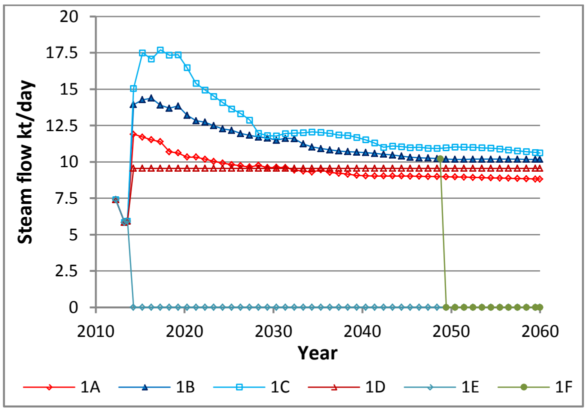

Figure 7: Steam flows for the future scenarios

Figure 6 shows the grid used in Model 2012/22816 with the location of the Waikato River and the resistivity boundary indicated. Six different future scenarios were simulated with the model to observe the effect of the proposed 35 year term of consent on the Ohaaki system (see Table 2). These scenarios were provided by Contact Energy.

The results of the scenarios are summarised in the total steam flow plots shown in Figure 7 and average enthalpies shown in Figure 8.

Scenarios 1A and 1B show similar steam flow trends, namely an initial increase then a steady decline which tapers off by about 2040. For Scenario 1B, the steam flow from 2040 onwards is ~10,200 t/day. For Scenario 1C the addition of make-up wells gives a large initial increase in steam flow as the reservoir tries to make up the 45,000 t/day of mass required, but the peak steam rate of 17,500 t/day cannot be maintained as the reservoir slowly cools after 2020 and the steam flow declines, reaching a similar steam flow to that for Scenario 1B by 2060.

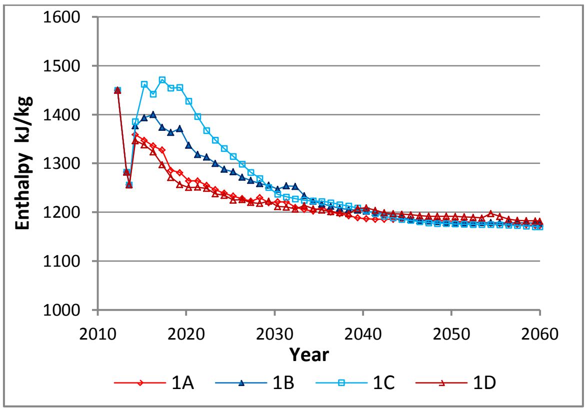

Figure 8: Average production enthalpy for the future scenarios

Other significant conclusions that were made as a result of the modelling study can be summarised as follows (O'Sullivan and Clearwater, 2013):

Scenario 1B. The take of up to 40,000 t/day of mass for Scenario 1B (the one selected by Contact as the application scenario) can be maintained over the modelling period (2013 to 2060). This demonstrates that the system can sustain 40,000 t/day of production up to and beyond the 35 year application period.

The available make-up wells are not all used and enthalpy remains almost constant from 2050 onwards. The deep pressure declines by up to 25 bar, but later recovers to a 20 bar decline where it levels off at 2060. The shallow pressure decline (at a depth of 350m) is much less at ~3 bar, recovering to less than 1 bar.

At 2060 the production enthalpy has stabilised at 1179 kJ/kg and temperatures in the deep reservoir at -1825 mRL (metres relative to sea level) are still high (over 300°C). An enthalpy of 1179 kJ/kg is well above 840 kJ/kg, the lowest useful enthalpy (the enthalpy at which there is enough energy for the well to discharge), hence there is a lot of useful heat still within the reservoir.

The main difference between Scenarios 1A, 1B and 1C (with mass takes of 35kt/day, 40kt/day and 45kt/day, respectively) is in the deep pressure behaviour on the West Bank with maximum declines of 8.8, 20.1 and 23.3 bars, respectively. Other parameters like shallow pressures and temperatures at all depths differ less between the scenarios.

Scenario 1C: The take of 45,000 t/day cannot be maintained over the modelling period as not enough make-up wells are available to sustain the required mass flow rate.

Scenario 1D: This scenario limiting the steam flow to 9,600 t/day (sufficient to run one IP turbine at full load), while at the same time enforcing a 40,000 t/day mass cap can be maintained over the modelling period. The mass flow increases over time to maintain the target steam flow, but it never reaches the 40,000t/day cap, instead reaching a maximum of ~37,000t/day by 2060.

Scenario 1E: A shut-down of production at 2013 is followed by a pressure build-up which stabilises by 2030.

Scenario 1F: A shut-down of production in 2048 is followed by a very similar pressure recovery to that observed for the 2013 shut-down scenario.

For both shut-down scenarios the temperature recovery is much slower than the pressure recovery.

By the end of the consent period, 91.8% of the original stored heat remains in the reservoir, and this figure drops to 90.5% by 2060 (assuming the production rate of 40,000 t/day continues past 2048 and on until 2060).

These conclusions not only enabled Contact Energy to determine the appropriate level exploitation to include in their resource re-consent, but are also used by decision-makers to support the ongoing management of the Ohaaki system.

4. CASE STUDY THREE: REINJECTION AT MENENGAI

The Menengai geothermal system is hosted in a ring-like caldera a short distance north of the city of Nakuru in Kenya. In 2010 it became the second field in Kenya to be developed for energy generation and a number of exploration wells and production wells have been drilled with maximum temperatures recorded in excess of 390°C. In 2013 a preliminary numerical model of the Menengai field was developed (Kipyego *et al.*, 2013) which highlighted the structural controls on the system and provided initial insights into its behaviour. The model also demonstrated that the standard TOUGH2 simulator was not adequate for modelling the supercritical conditions known to exist at depths below 3200m.

A new model was developed in which supercritical conditions were imposed in the upflow region of the bottom boundary. The model was run using the University of Auckland supercritical version of the TOUGH2 simulator (Croucher and O'Sullivan, 2008) with the air-water equation of state. The location of the Menengai system and the model grid used is shown in Figure 9. The modelled natural state temperatures in the main upflow of the Menengai system are shown in Figure 10, highlighting the importance of using the supercritical version of TOUGH2.

The possible production and reinjection scenarios that were investigated previously (Kipyego *et al.*, 2013) were investigated again using the supercritical model and the differences in the results are discussed below. The objective of the future scenario simulations was to understand the production potential of the Menengai system and to understand the impact of infield versus outfield reinjection. The scenarios are summarised in Table 3.

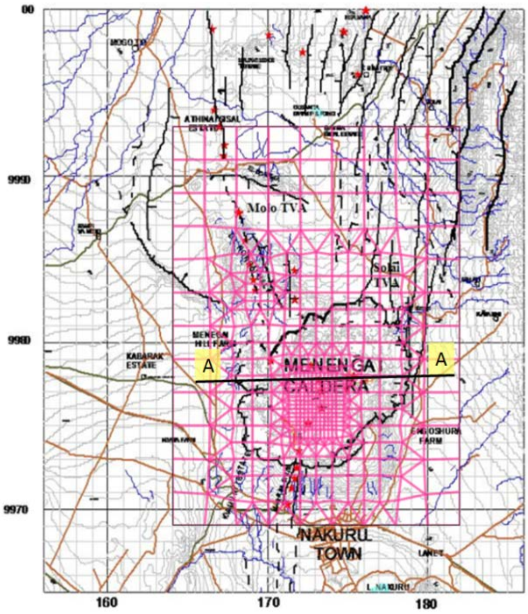

Figure 9: Plan view of the Menengai model grid. Location of the slice plot in Figure 10 indicated as Section AA.

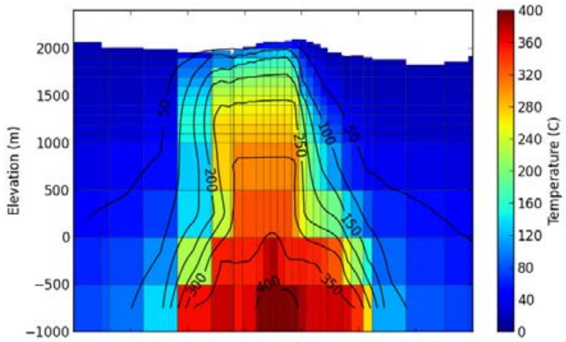

Figure 10: Model temperatures in the upflow of the Menengai system computed by the supercritical TOUGH2 simulator.

Table 3: Menengai Reinjection Scenarios (O'Sullivan *et al.*, 2015)

Scenario	Description
1	40 additional production wells added in three phases throughout Menengai caldera and Olrongai ridge.
2	Production wells added as in Scenario 1 with outfield reinjection of approximately 20% of the total mass produced.
3	Production wells added as in Scenario 1 with outfield reinjection of approximately 20% of the total mass produced.

The results for the predicted steam flow for all three scenarios, using both the standard model and the supercritical model, are plotted in Figure 11. The impact of accurately modelling the high temperatures found in the Menengai system is immediately apparent. Compared with the standard model the supercritical model predicts approximately 30% more steam from the same production scenario. The higher temperatures in the supercritical model mean that the average enthalpy is also predicted to be greater than in the standard model as shown in Figure 12. Also, because of the higher heat flow in the supercritical model, the average enthalpy of the fluid produced remains constant after 2025 for the no re-injection scenario, whereas it continues to decay when using the standard model.

The effect of re-injection in both models is similar, with infield re-injection providing the best pressure support and higher steam flow. Figure 11 shows that in the supercritical model the impact of the infield re-injection is slightly more significant than in the standard model but Figure 12 also shows that the average enthalpy declines faster as a result. This is due to the higher temperature rock in the supercritical model converting re-injected fluid into steam more effectively, but also cooling more rapidly.

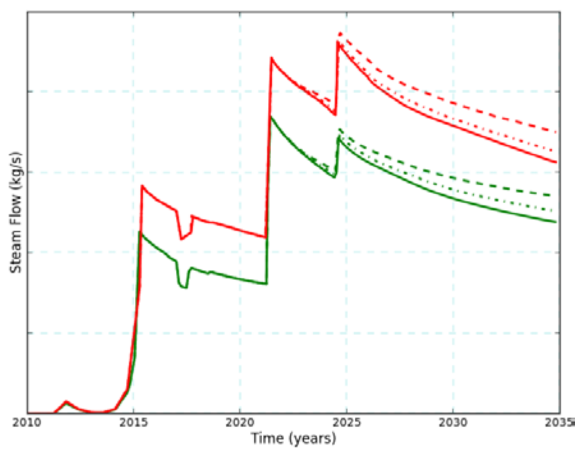

Figure 11: Predictions of steam flow for three different production scenarios for Menengai (O'Sullivan *et al.* 2015). The solid lines correspond to Scenario 1, the dashed lines to Scenario 2 and the dot-dashed lines to Scenario 3. The results obtained using the standard model are shown in green and the supercritical model in red.

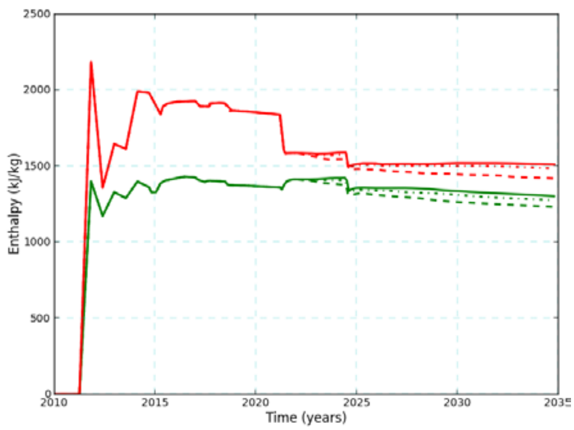

Figure 12: Predictions of average enthalpy for three different production scenarios for Menengai. Key as per Figure 11.

5. CASE STUDY FOUR: SUBSIDENCE

Subsidence as a result of extraction of geothermal fluids for energy production is a significant problem at many sites around the world. At Wairakei geothermal field in New Zealand, subsidence has occurred since the onset of production in the 1950s (Bromley *et al.*, 2013). Subsidence is non-uniform and reaches as much as 15m in a small area known as the Wairakei subsidence bowl. The subsidence there is attributed to a reduction of pore pressure in the Huka Falls Formation (HFF), which is composed of pumice breccia and mudstone.

Subsidence is a complex thermo-hydro-mechanical (THM) problem. It is characterized by interaction between the heat and mass transfer processes and the important reservoir parameters (i.e., permeability and porosity) and the mechanical behaviour of the host rock matrix (i.e., rock stress, strain and displacement). The decline of pore pressure due to production results in an increase in effective stress in the rock matrix and induces compaction. The cumulative effect of compaction appears at the surface as subsidence.

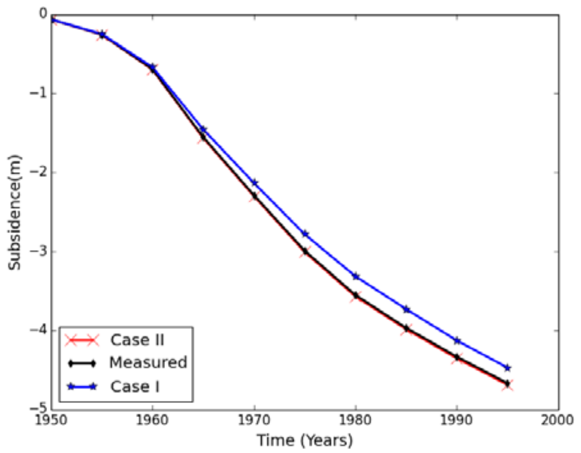

Figure 13: Total subsidence at the surface. Case I: using rock properties from Allis and Zhan (2000) and Case II: application of an elasto-plastic Cam-Clay Model (Koros *et al*., 2015).

Some studies of geothermal subsidence have used software that couples isothermal single phase flow in a porous medium with stress-strain analysis. For example, Allis and Zhan (2000) used a finite element code of this type to analyse subsidence at Wairakei and Ohaaki geothermal fields. The models of subsidence at Wairakei developed by Terzaghi and co-workers (White *et al*., 2005) used a finite-element package, PLAXIS, which simulates coupled compaction and isothermal fluid flow. The objective of the studies presented here was to investigate subsidence at Wairakei using a flow simulator capable of accurately representing two-phase, non-isothermal flow and a solid mechanics solver capable of representing complex rock mechanics. TOUGH2 was used for the heat and mass flow simulator and ABAQUS was the solid mechanics modelling package. The coupling was achieved through the use of Python scripting.

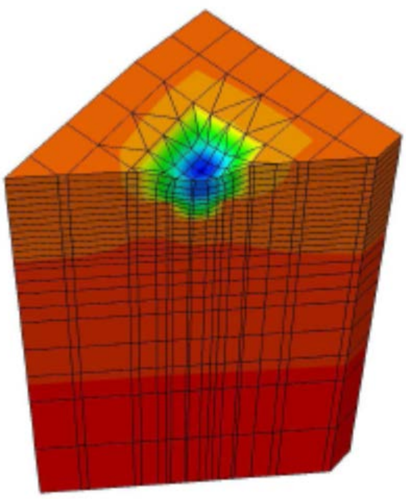

Figure 14: Section through the three-dimensional model of Wairakei subsidence bowl using coupled TOUGH2 and ABAQUS solvers (Yeh & O'Sullivan, 2007).

While these studies are ongoing, the preliminary results are very promising. Figure 13 shows how improvements over previously reported results (Allis and Zhan, 2000) have been made by including more realistic, complex rock mechanics (Koros *et al*., 2015). The coupling approach that has been developed at UoA is also robust and effective and can be applied to fully three-dimensional problems as shown in Figure 14. This has important implications for modelling subsidence on the scale of an entire geothermal system.

6. CASE STUDY FIVE: ENVIRONMENTAL IMPACT AT ROTORUA

The Rotorua geothermal field is situated at the southern margin of the Rotorua Caldera in the Taupo Volcanic Zone, New Zealand. The Rotorua system lies beneath a major city and has a unique abundance of natural features of great cultural, economic and scientific value. However from the 1950's onwards, intensive extraction of fluid and heat from over 900 shallow wells for commercial and industrial purposes resulted in a decline of the surface features. In 1986, a bore closure program was enforced and geyser activity and hot springs have rejuvenated progressively with some springs overflowing recently for the first time in over 30 years.

Numerical models of the Rotorua system have been developed at the UoA to study the response of surface features to production and reinjection. The models differ from previous models by having a much finer layer structure in the shallow zone and by including the unsaturated zone. This enables a better representation of near-surface mass and heat flow behaviour. They also include the complex structural and lithological structures associated with Rotorua's asymmetrical caldera collapse setting. The models have been calibrated against a large number of shallow temperatures, water table levels, the locations and magnitudes of surface activity and available pressure transients.

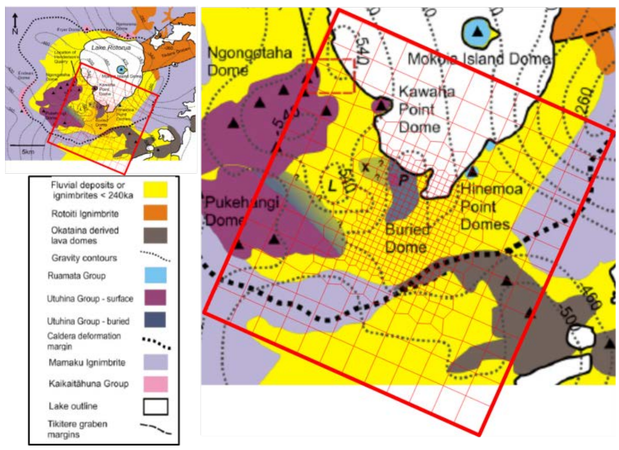

Figure 15: Geological map of the Rotorua Caldera, gravity anomaly contours (μN/kg) (Ashwell *et al*., 2013). UOA Model 3 grid shown in red (Ratouis *et al*., 2015).

a) b)

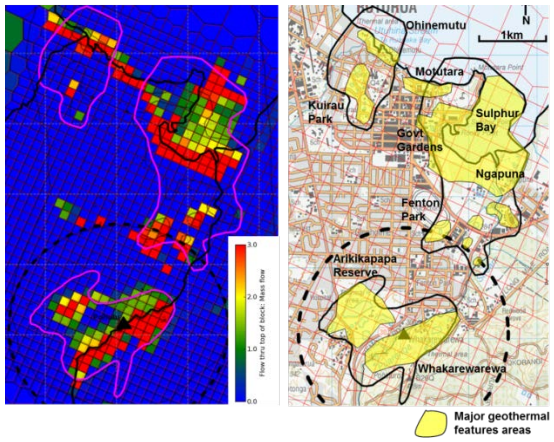

Figure 16: Natural State conditions: (a) UOA Model 4 surface mass flow (Ratouis *et al*., 2015) and (b) Rotorua city and major surface features (from topomap.co.nz).

Figure 16 shows that the natural state surface mass flow predicted by UoA Model 4 compares well with the actual locations of major surface features of the Rotorua system. In Figure 17 the model results for the response of monitor wells to production from the Rotorua system are compared with field data collected from the wells.

These results show that the model not only accurately represents the system's natural state, but also its transient response to both production and the borehole closure programme.

Currently more work is being carried out to calibrate the model, including more detailed information about the chemistry in the system. However a project has already been started with the local government, using the models to help monitor environmental changes in the system, to inform resource consent decisions and minimise environmental impacts.

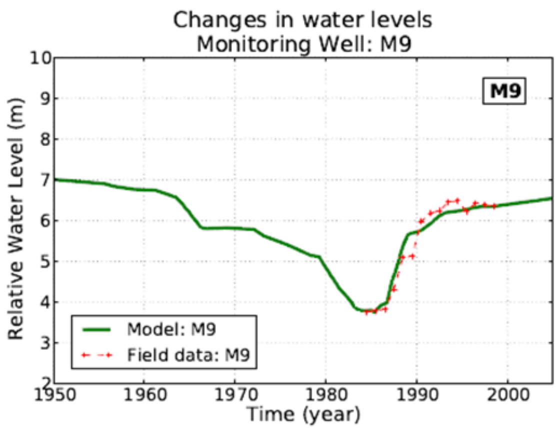

Figure 17: Modelled monitoring well relative water level response to production compared to field data (Ratouis *et al*. 2015).

7. CASE STUDY SIX: ENHANCED PERMEABILITY

In geothermal energy production, permeability can be enhanced or inhibited over time by various multi-physics controlled processes such as chemical species dissolution and precipitation, changes in stress or pore pressure, and by temperature effects such as thermal cracking. A wide range of methods has been used to numerically simulate permeability enhancement. Figure 18 shows an example of results obtained for enhanced permeability around an injection well from a simulation carried out at the UoA.

Models based on damage mechanics, discrete fracture mechanics, critical shear strain criteria, effective stress, and even empirical permeability multipliers have been proposed in the literature. Previous damage models do not account for the reversible nature of permeability enhancement. During injection, permeability may increase, but during shut-in time, permeability may decrease again. At the UoA work is being carried out to develop a reversible permeability enhancement methodology that is applicable to cyclic injection scenarios for geothermal energy production (Pogacnik *et al*., 2015).

The damage model has been implemented in coupled Thermo-Hydro-Mechanical (THM) simulations using AUTOUGH2, the UoA's version of TOUGH2, coupled with the solid mechanics code, ABAQUS. Coupling these two robust numerical solvers offers the potential to solve complex reservoir heat and fluid flow problems with advanced solid mechanics constitutive behaviour in large 3D simulations.

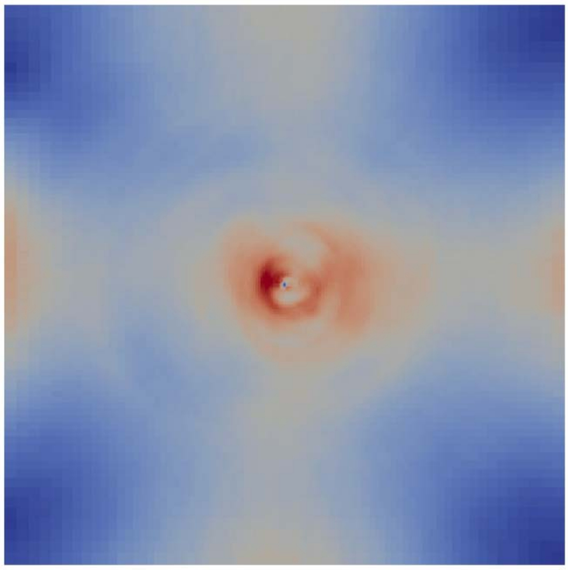

Figure 18: Simulation of permeability enhancement around an injection well (Pogacnik, *et al.*,2012).

We have a framework in place that allows for a Sequential Non-Iterative solution approach to couple the two codes. We are working to extend our simulation capability significantly on this front. Specifically, we seek to: include an iterative solution procedure that will better solve the equilibrated balance equations at each time step; utilize

ABAQUS extensive solid mechanics constitutive library and capabilities for complex rock behaviours; and allowing the user to perform solid mechanics analysis on a portion of the TOUGH2 grid, instead of the entire domain.

Work has also been carried out to calibrate numerical models against laboratory results from GNS Science's triaxial and Brazilian compression tests on samples of greywacke. Figure 19 shows the results of a simulation of a compression test that compares qualitatively well with the experimental results. More details of this simulation and other calibration simulations will be available in Pogacnik *et al*. (2014).

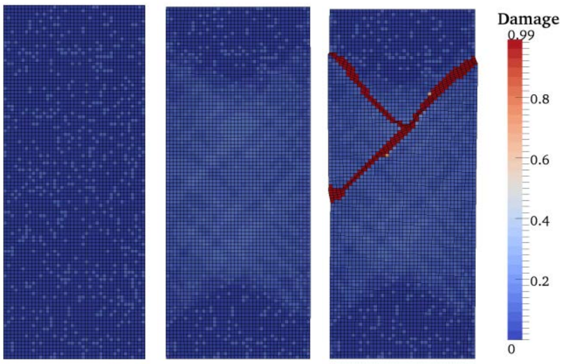

Figure 19: Simulation of laboratory experiments of rock failure in uniaxial compression tests (Pogacnik *et al*., 2014). Damage result at t = 0s, 10s, and 12s for a specimen with a random initial damage of 0.1 in 15% of the elements.

By developing a robust, accurate approach for coupling rock mechanics solvers capable of handling complex nonlinear behaviour with a non-isothermal, multiphase flow simulator, the UoA will be able to offer support to decision makers regarding strategies for permeability enhancement.

7. CONCLUSIONS

Six different case studies demonstrating the use of state-of-the-art reservoir modelling tools to support strategic decision-making have been presented. The case studies are from different countries and cover resource planning and optimisation for plant expansion and management, re-injection strategies, predicting subsidence, environmental sustainability and enhanced permeability. As the requirements of regulators and financers become more demanding it will become increasingly important for developers and operators to make use of these tools. Similarly for regulators and government bodies, increased public awareness means that they will be required to ensure the best practices and tools are used to monitor and regulate geothermal resources.

REFERENCES

Allis, R.G and Zhan, X.: Predicting subsidence at Wairakei and Ohaaki geothermal fields, New Zealand. *Geothermics*, 29. pp. 479-497. (2000).

Ashwell, P.A., Kennedy, B.M., Gravley, D.M., von Aulock, F.W. and Cole, J.W.: Insights into caldera and regional structures and magma body distribution from lava domes at Rotorua Caldera, New Zealand. *Journal of Volcanology and Geothermal Research*. pp. 187-202. (2013).

Bromley, C., Brockbank, K., Glynn-Morris, T., Rosenberg, M., Pender, M., O'Sullivan, M. and Steve, C.: Geothermal Subsidence Study at Wairakei-Tauhara, New Zealand. *ICE*, 166(GE2). pp. 211-223. (2013).

Carey, B., Alcaraz, S., Soengkono, S., Mroczek, E., Bixley, P., Rae, A., Lewis, B, Reeves, R. and Bromley, C.: *Ohaaki Geothermal Power Plant. Project Reference Report: Geoscientific and Reservoir Engineering Review*. GNS Science Consultancy Report 2011/273, 236p., (also Appendix C to Part B, the Assessment of Environmental Effects Report, submitted by Contact Energy to the Waikato Regional Council in support of an application for Resource Consents for the Ohaaki Geothermal Power Plant). (2013).

Clearwater, E.K., O'Sullivan, M.J. and Brockbank, K.: Recent Advances in Modelling the Ohaaki Geothermal Field, submitted to *Proc. 36th New Zealand Geothermal Workshop*, Auckland, New Zealand, 24-26 November (2014).

Croucher, A.E. and O'Sullivan, M.J.: Application of the computer code TOUGH2 to the simulation of supercritical conditions in geothermal systems. *Geothermics*, 37, p. 622-634.(2008).

Croucher, A.E.: PyTOUGH: a Python scripting library for automating TOUGH2 simulations. *Proc. 33th New Zealand Geothermal Workshop*, Auckland, New Zealand, 21-23 November (2011).

Croucher, A.E.: *PyTOUGH user's guide*, Department of Engineering Science, University of Auckland, Auckland, New Zealand, (2013).

Hedenquist. J.W.: The thermal and geochemical structure of the Broadlands -Ohaaki geothermal system, New Zealand. *Geothermics*, 19, pp. 151-185. (1990).

Kipyego, E., O'Sullivan, J. and O'Sullivan, M.: An initial resource assessment of the Menengai calder geothermal system using an air-water TOUGH2 model, *Proc. 35th New Zealand Geothermal Workshop*, Rotorua, November 18-20, (2013).

Koros, W., O'Sullivan, J.P., Pogacnik, J., O'Sullivan, M.J. and Ryan, G.: Comparison of coupled one-dimensional subsidence models, submitted to *Proc. World Geothermal Congress 2015*, Melbourne, Australia. (2015).

Lee, S. and Bacon, L.: Operational History of the Ohaaki Geothermal Field, New Zealand. Proc. World Geothermal Congress, Kyushu-Tohoku, Japan, 2000, pp. 3211-3216. (2000).

O'Sullivan, J.P., Kipyego, E., Croucher, A.E., Ofwona, C. and O'Sullivan, M.J.: A Supercritical Model of the Menengai Geothermal System, submitted to *Proc. World Geothermal Congress 2015*, Melbourne, Australia. (2015).

O'Sullivan, M.J. and Clearwater, E.: Ohaaki Geothermal Power Plant Project Reference Report: Reservoir Modelling. Uniservices Report, 169 p., (also Appendix D to Part B, the Assessment of Environmental Effects Report, submitted by Contact Energy to the Waikato Regional Council in support of an application for Resource Consents for the Ohaaki Geothermal Power Plant). (2013).

O'Sullivan M.J. and Yeh A.: *Wairakei-Tauhara Modelling Report*. Uniservices and Department of Engineering Science, University of Auckland. (2007). (http://www.mfe.govt.nz/rma/call-in-temihi/board-of-inquiry/evidence/11b-professor-osullivan.pdf)

O'Sullivan, M.J.: A history of numerical modelling of the Wairakei geothermal field. *Geothermics*, 38(1), pp. 155-168. (2009).

O'Sullivan M.J. and Yeh A.: *Wairakei-Tauhara Modelling Report*. Uniservices and Department of Engineering Science, University of Auckland. (2010). (http://www.contactenergy.co.nz/web/pdf/environmental/P4ReservoirModellingReport.pdf)

Pogacnik, J., Leary, P., and Malin, P.: Physical/Computational Framework for EGS *in situ* Fracture Stimulation, *Proc. 34th New Zealand Geothermal Workshop*, Auckland, New Zealand, 19-21 November (2012).

Pogacnik, J., McNamara, D., O'Sullivan, M.J., and O'Sullivan, J.P.: A Damage Mechanics Approach to Modeling Failure and Permeability Evolution in Greywacke Rock, submitted to *Proc. 36th New Zealand Geothermal Workshop*, Auckland, New Zealand, 24-26 November (2014).

Pogacnik, J., O'Sullivan, M.J., and O'Sullivan, J.P.: Linking TOUGH2 and ABAQUS to Model Permeability Enhancement Using a Damage Mechanics Approach, submitted to *Proc. World Geothermal Congress 2015*, Melbourne, Australia. (2015).

Pruess, K., Oldenburg, C. and Moridis, G.: *Tough2 User's Guide, Version 2.0*. Lawrence Berkeley National Laboratory Report LBNL-43134. (1999)

Rae,A.J., Rosenberg, M.D., Bignall,G., Kilgour, G.N. and S. Milicich, S.: Geological results of production well drilling in the western steamfield, Ohaaki geothermal system: 2005-2007. *Proc. 29th New Zealand Geothermal Workshop*. (2007).

Ratouis, T., O'Sullivan, M.J., and O'Sullivan, J.P.: An Updated Numerical Model of Rotorua Geothermal Field, submitted to *Proc. World Geothermal Congress 2015*, Melbourne, Australia. (2015).

Wellmann, F. J., Croucher, A., and Regenauer-Lieb, K.: Python scripting libraries for subsurface fluid and heat flow simulations with TOUGH2 and SHEMAT. *Computers & Geosciences*, *43*, pp. 197-206. (2012).

Wellmann, J. F., Finsterle, S., and Croucher, A.: Integrating structural geological data into the inverse modelling framework of iTOUGH2. *Computers & Geosciences*, pp. 95-109, (2014).

White, J.P., Lawless, V.J., Terzaghi, S., and Okada, W.: Advances in Subsidence Modelling of Exploited Geothermal Fields. *Proc. World Geothermal Congress 2005*, Antalya, Turkey. pp. 105-111. (2005).

Yeh, A., Croucher, A. E. and O'Sullivan, M. J.: Recent Developments in the AUTOUGH2 Simulator. *Proc. TOUGH Symposium 2012*, Lawrence Berkeley National Laboratory, Berkeley, California, September 17-19 (2012).Yeh, A., Croucher, A. E. and O'Sullivan, M. J.: Recent Developments in the AUTOUGH2 Simulator. *Proc. TOUGH Symposium 2012*, Lawrence Berkeley National Laboratory, Berkeley, California, September 17-19 (2012).