Modelling source networks with the Waiwera geothermal flow simulator

Adrian Croucher[1], Angus Yeh[1], Michael O'Sullivan[1] and John O'Sullivan[1]

[1]Department of Engineering Science, University of Auckland, Private Bag 92019, Auckland 1142, New Zealand

a.croucher@auckland.ac.nz

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ABSTRACT

Models of production history and future scenarios for real geothermal fields generally require an interconnected network of source and sink terms to represent production wells (including make-up wells), groups of these wells, separators and reinjection back into the reservoir. The AUTOUGH2 flow simulator includes a system for doing this, but it is somewhat inflexible, partly due to limitations imposed by the input file format.

We have recently added source network modelling capability to the Waiwera flow simulator, using a completely redesigned system which offers greater flexibility and new possibilities, including an improved way to represent multi-feed production wells. It also works in parallel both on shared-memory machines (e.g. desktops) and distributed-memory machines (e.g. high-performance computing clusters).

1. INTRODUCTION

Numerical models of geothermal reservoirs use source terms to represent fluid and/or heat being withdrawn from or injected into the reservoir, for example to simulate wells, springs or flux boundary conditions. Simpler source terms like springs may act independently of other sources, but more complex ones can be interconnected – i.e. the flow rate in one source depends on the flow rates in some of the other sources.

An obvious example is that of reinjection, in which fluid from some of the production wells (e.g. the separated geothermal water) is reinjected back into the reservoir. In this case the flow rates in the sources representing the reinjection wells depend directly on the flow rates in the production well sources.

Another important example is the simulation of a group of production wells (perhaps representing a borefield) in a future scenario model, in which a limit is imposed on the total flow and/or steam flow from the group. In this case, "make-up wells" may be used to ensure the total flow is as close to the limit as possible, with more make-up wells being brought online as flows in the already-producing wells decline over time. Such an approach has been used for many years to model future scenarios for e.g. the Wairakei geothermal field (O'Sullivan et al., 2009). Clearly, the flows in the sources representing the make-up wells depend on the flows in the other sources in the group.

When sources are interconnected in this way, they form a "source network", and the reservoir simulator used must have capability for simulating this network. In this paper, we briefly discuss the source network modelling capability available in other simulators before describing the source network functionality recently added to the Waiwera simulator. We then show results from benchmark tests and a full-scale application demonstrating its performance.

2. SOURCE NETWORKS IN OTHER SIMULATORS

Neither the TOUGH2 simulator (Pruess et al., 1999) or its successor TOUGH3 (Jung et al., 2017) offer capability for modelling source networks. The University of Auckland maintains a fork of TOUGH2 called AUTOUGH2 (Yeh et al., 2012), which includes a number of features specific to geothermal reservoir simulation, including some additional generator types for modelling groups of make-up wells and reinjection wells. While these have been used for modelling complex production/ reinjection scenarios in the Wairakei model, they have limitations, many of which are imposed by the inflexible format of the AUTOUGH2 input file.

Make-up wells are represented in AUTOUGH2 using the MAKE, DMAK and DMAT generator types (for prescribed-rate and deliverability make-up wells). The TMAK generator type does not represent a source but is used as a way of defining a group of make-up wells and total mass and/or steam limits for the group.

It is possible to define multiple groups, but because of the way the input is structured it is necessary to define the make-up wells in a particular order, and it is not possible to define hierarchical "nested" groups, i.e. groups that contains other sub-groups. Sometimes a production scenario will have total mass or steam limits on a group that change over time, but the TMAK generator type allows only fixed limits, so this can be simulated only by splitting up the model run into stages. The DMAK and DMAT generators also lack some of the options available in other deliverability generator types (e.g. specifying time-dependent productivity index, as in the DELG, DELT and DELW generators).

Reinjection sources are represented by the FINJ, PINJ, IMAK and RINJ generator types. These reinject a specified amount of flow from the total available for reinjection, either at a fixed rate (FINJ), a proportion of the total (PINJ), a flow rate dependent on reservoir pressure (IMAK) or a proportion of the remainder left over from the FINJ, PINJ and IMAK sources (RINJ). As for groups, because of the input structure it is not possible to define more complex nested reinjection networks. Neither is it possible to specify time-dependent reinjection parameters (e.g. reinjection flow rates or proportions).

The Volsung simulator also has capability for modelling surface networks, including make-up wells and reinjection (Clearwater and Franz, 2019).

3. SOURCE NETWORKS IN WAIWERA

Waiwera is a new parallel, open-source geothermal flow simulator developed in New Zealand (Croucher et al., 2019, Croucher et al., 2020), building on our experience developing and maintaining AUTOUGH2 but designed to overcome many of its limitations. As part of the ongoing

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development of Waiwera, source network modelling capability has recently been added.

In defining the scope of this work, it was decided at an early stage not to attempt to include capability for simulating completely general source networks. Such capability would amount to integrating a complete above-ground non-linear pipe network solver into Waiwera. It was felt that, if this level of complexity was required, it would be better to have Waiwera communicate with an existing dedicated above-ground network solver. In our experience such complexity is seldom necessary: a more flexible version of AUTOUGH2's source network capability will usually be sufficient.

Whereas AUTOUGH2 implicitly defines its source network in the model input as part of the list of sources, Waiwera introduces a separate section in the model input for the network, with two sub-sections for source groups and reinjection.

3.1 Source groups

A source group is defined simply via a list of its inputs (identified by name), which can be sources, other groups or a mixture of the two. Hence, nested group structures are possible. Unlike AUTOUGH2, Waiwera does not have any concept of source "types" (different source behaviours instead being achieved by more flexible "source controls"), so there are no restrictions on which sources can be part of a group.

3.1.1 Group limiters

A group may have one or more "limiters" with specified maximum values of total, separated steam or separated water flow. The limits can be time-dependent, specified using tables of values with configurable interpolation (piecewise linear or step).

When the group flow exceeds the specified limit, the flows in its inputs are scaled down so that the limit is met. If any of the inputs are also groups, this procedure is carried out recursively. If an input is a source, then its previously-computed flow rate (from e.g. tables of values vs. time, deliverability or source limiters) is treated as a capacity and the actual flow rate is scaled down.

3.1.2 Group scaling

The group inputs can be scaled down in one of two ways: uniformly or progressively. In uniform scaling, all inputs in the group are scaled down by the same factor. This is appropriate, for example, when using a source group to represent a multi-feed well.

In progressive scaling, the inputs are scaled down one at a time, starting from the end of the list, until the limit is met. This is appropriate for groups of make-up wells, where sources with zero flow rate represent wells that are shut in or not yet drilled.

3.2 Separators

Accompanying the introduction of source networks in Waiwera is a revision of the treatment of separators. Previously these were treated as a kind of source control, used only to attach limiter source controls if a limit on separated steam or water was required at a well.

Now, separators can be defined on sources or source groups. They produce output on separated steam or water flows and enthalpies, regardless of whether any limiters are being used. A source group separator can be used when simulating a group of production wells that feed into a common separator, or a multi-feed well, represented by a source group, with a single separator taking flow from all feeds. Multi-stage separators (with arbitrary numbers of stages, e.g. two-stage flash) may also now be used.

3.3 Reinjection

Waiwera now also allows the user to define "reinjectors", which are in many ways the opposite of groups: they take separated water and steam flows from a single input and distribute them among multiple outputs. The input can be a production source, a source group or another reinjector, while the outputs can be injection sources or other reinjectors. This makes it possible to define more complex nested reinjection networks.

Outputs can deliver either separated water or steam (condensate). The flow rate at an output can be specified either as a rate or as a proportion of the input flow. In either case, these can be time-dependent. Within each output category (water or steam) the input flow is distributed among the outputs progressively, in the order they are specified. If there is not enough input flow for the specified outputs, then some of the later outputs will have zero flow rates.

If the output is to a reinjection source, and the flow rate in that source has already been computed from a source control (e.g. when injecting against a pressure) then that rate is treated as a capacity. Hence, output flow rates can be specified at the reinjector output itself, or the source, or both (in which case the actual flow rate will be the minimum of the two). The output enthalpy can be specified (if this is omitted, the enthalpy is taken from the input).

A reinjector also has a special output called the "overflow", which will flow if there is more fluid entering the reinjector than can be delivered through its outputs. The amount of overflow is recorded in the simulation output, and can also be optionally directed to an injection source or another reinjector.

3.4 Parallel implementation

Waiwera is parallelised via the "Message Passing Interface" (MPI) to run on shared- or distributed-memory parallel computers (e.g. desktop PCs or HPC compute clusters). It uses a "domain decomposition" technique in which the model mesh is divided up into parts and each parallel process works on its own part.

This makes the implementation of source networks challenging, because it means that the individual sources in a group may not all be on the same parallel process. Some parallel communication is needed between processes to compute, for example, the total flow rate in a group. This is further complicated in the case of nested groups, where some of the inputs are also groups and the total flow rate must be computed recursively.

MPI uses the concept of a "communicator", which is used to share data between processes, either all the processes or a subset of them. Waiwera source groups define their own MPI communicators for sharing data between the processes in the group. One of the processes is designated the "root" process for the group and coordinates tasks such as computing total flows and sending results to output. The challenges for reinjectors are similar and are solved in much the same way.

4. TESTS AND APPLICATIONS

Here we demonstrate the performance of Waiwera's source network modelling capability using two new benchmark test models (for make-up wells and reinjection) added to the Waiwera benchmark test suite, and the Wairakei reservoir model.

4.1 Make-up well benchmark test

This benchmark test simulates idealised production from a group of make-up wells. It has a simple 10-cell 1-D vertical column mesh, 1 km deep, with an atmospheric boundary at the top and hot water (240 °C) injected at 10 kg/s at the bottom.

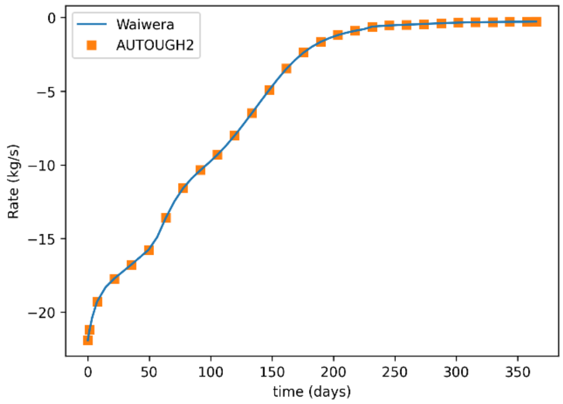

Figure 1: Well 1 rate history for make-up well benchmark test

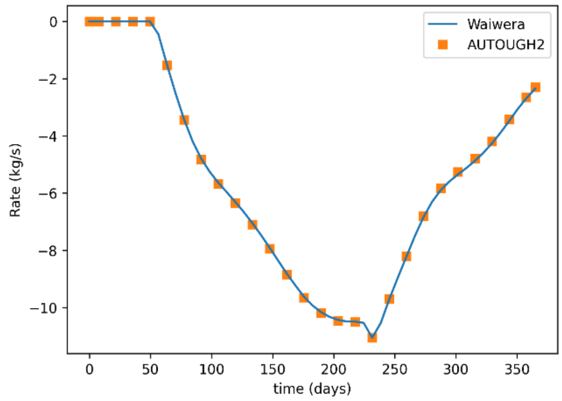

Figure 2: Well 2 rate history for make-up well benchmark test

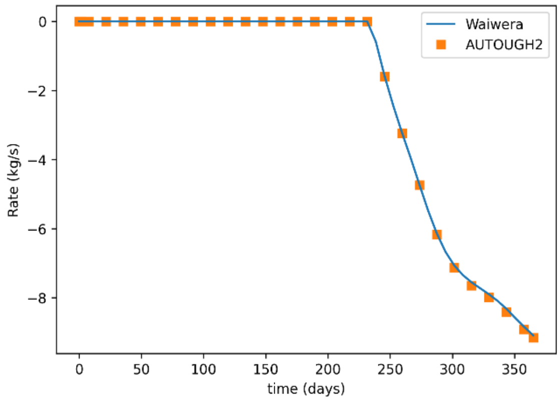

Figure 3: Well 3 rate history for make-up well benchmark test

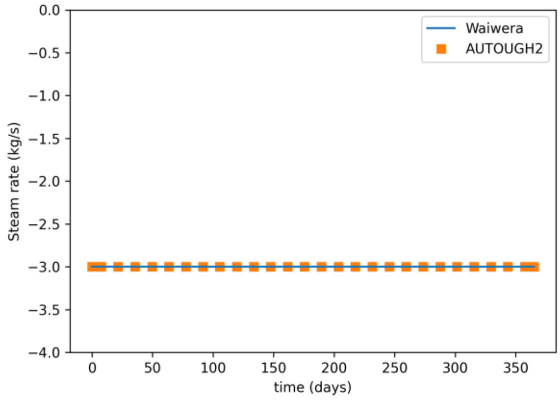

Figure 4: Total produced steam flow history for make-up well benchmark test

Starting from steady-state conditions (which contain a steam zone near the surface), production is simulated for one year with production wells at 180 m, 250 m and 350 m depths, all on deliverability. A total separated steam limit of 3 kg/s is imposed on the group of three wells and progressive scaling (see section 3.1.2) is used to achieve it.

Figures 1 – 3 show the flow rates vs. time in the three production wells, computed by Waiwera and AUTOUGH2. Because of the progressive scaling, only well 1 is producing at first, but its flow rate declines as a result of drawdown and by about 55 days it can no longer produce the required steam. At this point well 2 starts producing. However, by about 240 days it also declines to the point where well 3 must be introduced. Figure 4 shows that the total separated steam flow rate from all three production wells is exactly -3 kg/s, in accordance with the imposed steam limit. The agreement between the Waiwera and AUTOUGH2 results is excellent.

4.2 Reinjection benchmark test

This benchmark test simulates various types of reinjection and uses the same mesh as the make-up well benchmark test (see section 4.1). It also uses the same three production wells, but without a steam limit imposed. Instead, some of the produced fluid is reinjected via four injection wells, all at a depth of 20 m:

- well 4 reinjects steam condensate at a fixed rate of 1.5 kg/s
- well 5 reinjects 10% of the total steam condensate from production
- well 6 reinjects separated geothermal water against the reservoir pressure, with a reference pressure of 9 bar and an injectivity coefficient of 3×10^{-6} m.s
- well 7 reinjects 5% of the separated geothermal water remaining after reinjection into well 6

Steam condensate is reinjected at an enthalpy of 85 kJ/kg and separated geothermal water at 440 kJ/kg.

Figures 5 – 7 show the flow rates vs. time in the injection wells 5, 6 and 7 (results for injection well 4 are not shown as it has a constant rate). The flow rate in well 5 declines with time as it is proportional to the total produced steam flow, which also declines due to drawdown. Similarly, the flow rate in well 7 declines as it depends on the total amount of separated geothermal water produced.

Well 6 does not flow until its pressure drops below 9 bar, after about 100 days. Its production rate generally increases as the reservoir pressures continue to drop.

The agreement between the Waiwera and AUTOUGH2 results is excellent in all wells.

4.3 Wairakei reservoir model

Waiwera's source network modelling capability was tested on a recent experimental version of the Wairakei reservoir model. This version of the model contains approximately 65,000 cells and uses an air-water equation of state. The permeability structure is complex, having been refined over many years of model development, and contains nearly 600 rock types.

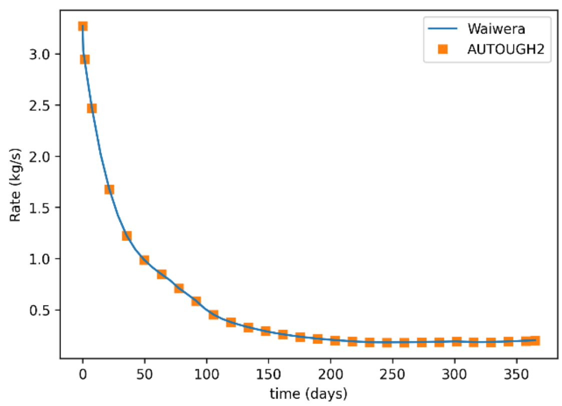

Figure 5: Well 5 rate history for reinjection benchmark test

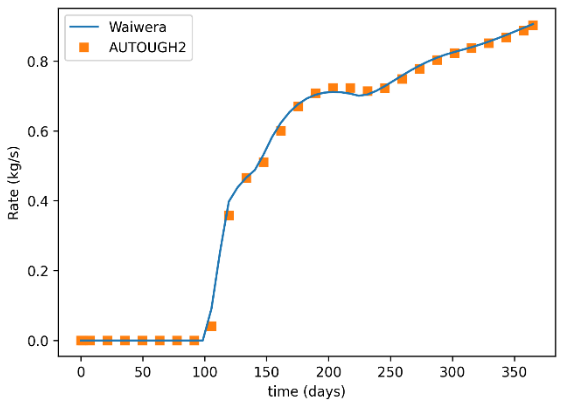

Figure 6: Well 6 rate history for reinjection benchmark test

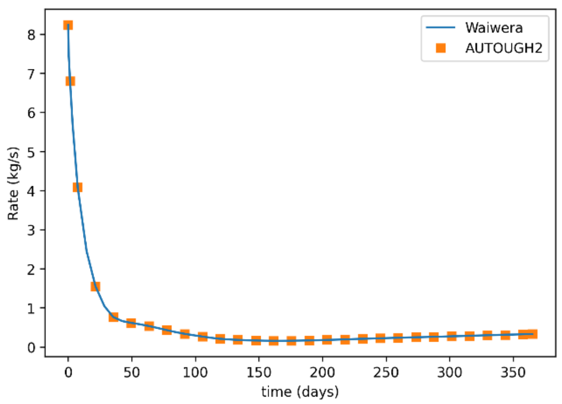

Figure 7: Well 7 rate history for reinjection benchmark test

However, this version of the model has not yet been fully calibrated, so the results presented here should not be taken as an accurate representation of the system's behaviour. Rather, the aims were to test Waiwera's new source network modelling capability on a full-scale model with a complex source network, to show that Waiwera can reproduce the results from AUTOUGH2 and to demonstrate Waiwera's improved performance.

A future scenario model was selected, as these contain both make-up wells and reinjection. Again, this was not intended to be a completely realistic scenario but rather one with a level of complexity similar to that of actual Wairakei future scenario models currently in use.

This scenario model has approximately 600 production well sources in four source groups. These in turn supply fluid to four reinjectors which contain approximately 870 reinjection sources between them (some injecting water and some steam condensate). Most of the reinjection sources inject against reservoir pressure (IMAK generators in the AUTOUGH2 version of the model).

For the purpose of comparing results between AUTOUGH2 (version 2.46, with the EWA equation of state) and Waiwera, the first 3.4 years of the scenario was run. Both model runs were carried out on a desktop PC with a 12-core Intel Xeon E5-2670 processor. Waiwera was run in parallel using 8 processes.

For AUTOUGH2 (which runs only in serial), the model run took 6 hours and 45 minutes to complete. By comparison, the Waiwera run took only 17 minutes (about 23 times faster). This is partly because Waiwera is parallelised, but also because it took significantly fewer time steps than AUTOUGH2 (638 steps instead of 1505).

Figures 8 and 9 show the resulting time history plots of total steam production and total reinjection over the model, for both AUTOUGH2 and Waiwera. Figures 10 – 12 show time history plots of reinjection in three different reinjection areas, Karapiti, Poihipi and Otupu. Between the start and end times, results are shown at the beginning of each year.

The agreement between the AUTOUGH2 and Waiwera results is very good. Modelled pressures and temperatures in the reservoir (not shown here) were also compared between the two simulators, with pressure differences less than around 1.5% and temperature differences less than 0.2%. Some minor differences in the solution are expected because AUTOUGH2's EWA EOS is quite different from Waiwera's air-water EOS (using different primary variables and air thermodynamics). Flow rates in individual production and injection wells were also compared and were in good agreement.

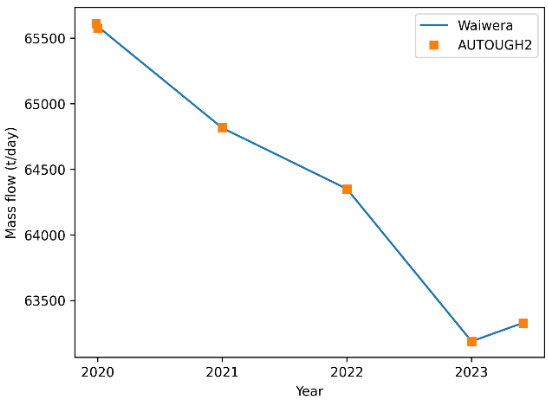

Figure 8: Total steam production vs. time for Wairakei future scenario model

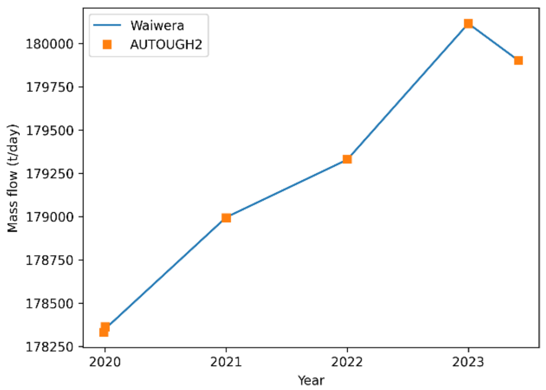

Figure 9: Total injection vs. time for Wairakei future scenario model

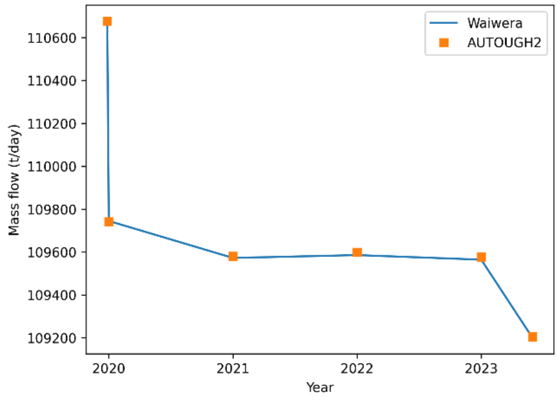

Figure 10: Total reinjection to Karapiti for Wairakei future scenario model

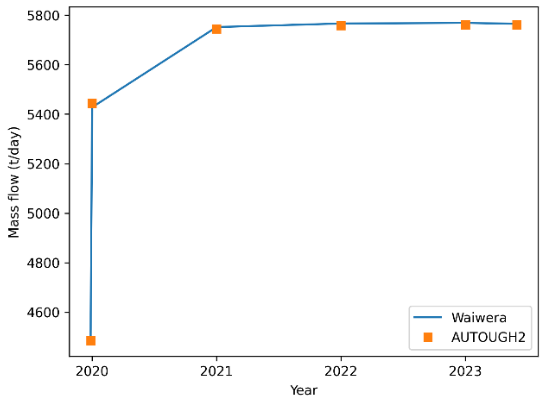

Figure 11: Total reinjection to Poihipi for Wairakei future scenario model

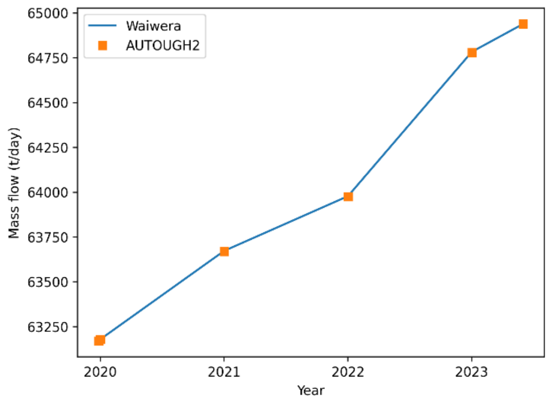

Figure 12: Total reinjection to Otupu for Wairakei future scenario model

5. CONCLUSION

The ability to model source networks, including groups of production sources, multi-feed wells and reinjection networks, has been added to the Waiwera geothermal flow simulator. Waiwera's source network modelling capability offers considerably more flexibility than the limited capability included in AUTOUGH2. In particular, "nested" groups and reinjectors may be used, and most reinjection parameters can be made time-dependent.

Results from benchmark tests and application of the code to a complex, full-scale Wairakei future scenario model demonstrate good agreement with AUTOUGH2 results. The Wairakei model results also demonstrate Waiwera's greatly improved computational efficiency compared with AUTOUGH2.

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REFERENCES

Croucher, A., O'Sullivan, M., O'Sullivan, J., Yeh, A., Burnell, J. and Kissling, W.: An update on the Waiwera geothermal flow simulator: development and applications. *Proc. 41st NZ Geothermal Workshop,* 25 – 27 November 2019, Auckland, New Zealand (2019).

Croucher, A., O'Sullivan, M., O'Sullivan, J., Yeh, A., Burnell, J. and Kissling, W.: Waiwera: A parallel open-source geothermal flow simulator. *Comp. Geosci*. 141 (2020).

Clearwater, J. and Franz, P.: Introducing the Volsung geothermal simulator: features and applications. *Proc. 41st NZ Geothermal Workshop,* 25 – 27 November 2019, Auckland, New Zealand (2019).

Jung, Y., Pau, G., Finsterle, S. and Pollyea, R.: TOUGH3: a new efficient version of the TOUGH suite of multiphase flow and transport simulators. *Comp. Geosci*. 108, 2 - 7 (2017).

O'Sullivan, M.J., Yeh, A. and Mannington, W.I.: A history of numerical modelling of the Wairakei geothermal field. *Geothermics* 38, 155 – 168 (2009).

Pruess, K., Oldenburg, C. and Moridis, G.: *TOUGH2 user's guide*, version 2.0. LBNL-43134, Lawrence Berkeley National Laboratory, Berkeley, California (1999).

Yeh, A., Croucher, A. and O'Sullivan, M.J.: Recent developments in the AUTOUGH2 simulator. *Proc. TOUGH Symposium 2012*, Berkeley, California, September 17-19 (2012).