Using ITOUGH2 To Improve Geothermal Reservoir models

Stephen P. White, Roger M. Young, Warwick M Kissling
Industrial Research Ltd., P.O. Box 31310 , Lower Hutt, New Zealand

In this paper we will present two examples of the use of inverse modelling as an aid to the development of a geothermal reservoir model. The first example takes an existing model of the Kawerau geothermal reservoir and attempts to improve it using ITOUGH2. For the second example we intended using inverse modelling as part of our modelling strategy and this influenced the model development. In this example we develop a model of the Tauhara geothermal field. It is a little unusual in that some of the data used for parameter refinement is changes in reservoir conditions in response to production from an adjoining reservoir (Wairakei).

1. Kawerau Reservoir Model

Kawerau geothermal field is the most northeasterly of the major land-based geothermal systems of the Taupo volcanic Zone of New Zealand The field lies between the andesite volcano of Mt Edgecumbe and the rhyolite/dacite domes known as the Onepu hills, and is centred on the flood plains of the Tarawera river (Figure 1).

The TOUGH2 model that formed the basis of the inverse modelling described here was developed over a number of years by several people. This development is summarised in White *et al.* (1997) and will not be repeated in detail here.

1.1 Model Description

The TOUGH2 model developed to represent the Kawerau reservoir covers an area 10 km 10 km encompassing the most recent resistivity boundary and extending as far south as Mt Edgecumbe. Vertically the model extends from deep in the greywacke basement, at a depth of 3.5 km, to the surface.

The model is divided into 15 horizontal layers of varying thickness. Each layer is divided into a number of blocks. The spatial resolution of the model is controlled by the size of blocks in a layer and the thickness of the layer.

The geology of the drilled area of the field is very complex. Basement greywacke is overlain by at least 13 different units, including rhyolites, breccias, andesites, tuffs, sediments and ignimbrites. Currently production is from fractured greywacke or andesite. It is believed the Huka sediments and ignimbrite act as aquacludes over areas of the field. Where possible, geological data from Allis *et al.* (1993) were used to assign a rock type to each element. Where no geological information is available, rock types assigned to an element represent a best guess of the correct type.

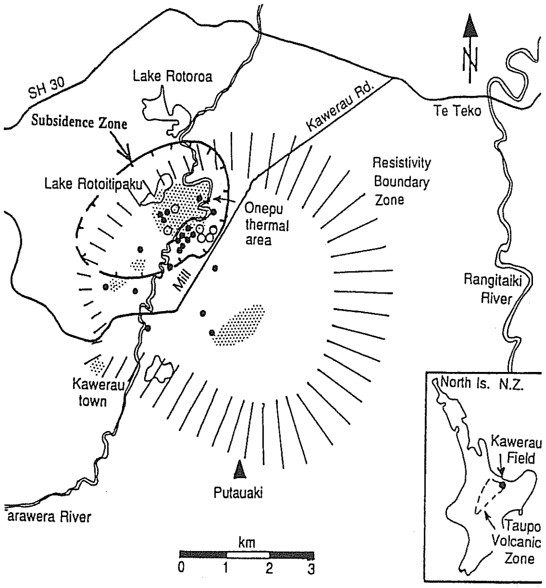

Figure 1: The Kawerau geothermal field.

It is believed that a deep hot source exists in the vicinity of Mt Edgecumbe, with the hot source fluid moving predominantly through faults and permeable zones in the basement greywacke, and mixing with cooler waters flowing horizontally across the field. Secondary permeability is provided by fracturing of brittle rock types and this provides a pathway for interaction between the geothermal fluids and larger volumes of rock than is accessed by the known faults in the system.

Known faults have been included in the model and are represented as areas of enhanced permeability. It is assumed that rocks outside the resistivity boundary have not been subjected to the same thermal stresses as those within the boundary, and consequently permeabilities will not have been enhanced by hydrothermal fracturing.

2. The Natural State

2.1 Manual Method

As a first step in assigning rock properties, a rock type (eg, andesite, greywacke, etc) was assigned to each model element. Values for permeability, porosity and density were assigned to each rock type. These values were obtained from previous estimates of reservoir properties from interference tests and the like. Where no information was available the values chosen were simply guesses.

Grant [Mongillo, Chapter 14] has analysed all the early pressure and temperature measurements from Kawerau and adjusted the data to one of three reference levels at 750 metres, 1050 metres, and 1400 metres below sea level. This data of Grant, together with data not available to Grant, was used to adjust the permeabilities.

The procedure followed was to run the model until a steady state was reached then a 'goodness of fit' to measurement was calculated. This goodness of fit (SS) is defined by

$$SS = \sum_{i=1} \frac{\left| X_i - X_{meas} \right|}{X_{meas}} \tag{1}$$

where X_i is the calculated value of pressure of temperature and X_{meas} is the measured value. SS is the average relative error in the calculated value. In all 55 data points were included in the match. Permeabilities and inflows were adjusted to approximately minimise SS. The final value achieved for the model represents an average error in calculated values of 3%. However it must be remembered that data are only available over a small part of the modelled volume.

2.2 Match to measured data

After some experimentation the match to measurement shown in Figure 2 was obtained. Apart from one outlier (KA26) with a 12% error in pressure at 750 metres, almost all the other errors are less than 3 % and are distributed more or less evenly about zero. KA26 lies in the south west of the field, well separated from most of the other wells (apart from KA29) and has very poor permeability. There is also an outlier in the calculated temperatures at the nearby KA29.

In this case of temperatures the errors are also reasonably evenly distributed about zero and in most cases are within ± 5%. There is an obvious outlier at 1050 metres with an error of 17%. This is in well KA29 which is located in the south west of the field 80 metres north of KA26 (the location of the largest error in pressure).

3. Inverse Modelling

ITOUGH2 formalises the intuitive approach described in section 2.1 by minimising an objective function calculated from the differences between the model solution and measured data. There are several functional forms of the objective function available, the advantages of the different forms are discussed in Finsterle (1993). For the work described here we have used the default objective function which is a **quadratic** function of the residuals. Note that for the manual method we used a **linear** objective function. The effect of the quadratic objective function is to emphasise the importance of outliers on the objective function. In hind site, it would have been better to choose a linear objective function or one based on a robust estimator as this would have made the comparison with the manual method easier.

We used the same model as in the manual method and allowed ITOUGH2 to vary ten permeabilities in order to reduce the objective function. We used an option that initially calculated the sensitivities of all the parameters and only those with large sensitivities were varied in an attempt to reduce the objective function. All the sensitivities were recalculated each 3 iterations. This reduced the original ten parameters to about five for most of the calculation. After 16 iterations (requiring about 140 TOUGH2 runs) the objective function was reduced to 61% of its original value. While this point was not regarded as a minimum by ITOUGH2 the results presented in this paper are taken from there

From the sensitivities calculated by ITOUGH2 we find the most important parameter is the vertical permeability of the Huka formation (ROCK07) which provides a partial cap to the field at around 500 meters depth. The other important parameters are the vertical permeability of the Opnoke ignimbrite (ROK09) which provides a flow barrier in the southern part of the field and the horizontal permeability in the basement greywacke (ROK03).

Also provided are estimates of the standard deviation for the distributions of the estimated parameters which provide a range within which we expect the parameter to lie. For the three most important parameters the estimated range (3σ) is given in Table 1.

Parameter	Minimum	Mean	Maximum
ROK07z	4.2×10^{-16}	$6.4 \times10\wedge^{-16}$	9.8×10^{-16}
ROK09z	3.8×10^{-16}	6.8×10^{-16}	1.3×10^{-15}
ROK03xy	1.1×10^{-14}	1.2×10^{-16}	2.8×10^{-14}

Table 1: Range estimates for important parameters.

Unfortunately the very large amounts of computer time required for a ITOUGH2 run precluded any experimentation with different optimisation functions. We have also added a number of extra data points for the ITOUGH2 run. These were added in an attempt to improve the vertical temperature distribution in the south of the field. Unfortunately this means a direct comparison between Figures 2 and 3 cannot be made.

the manual method easier.

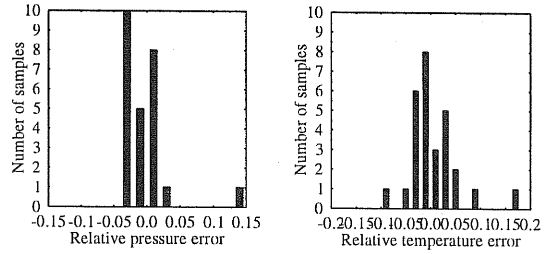

Figure 2: Relative errors in pressure and temperature (manual method)

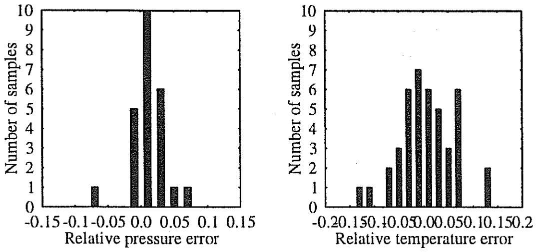

Figure 3: Relative errors in pressure and temperature (ITOUGH method)

4. Tauhara Geothermal Field

The Tauhara field lies close to Lake Taupo in the Taupo Volcanic Zone (Figure 4). We envisage Tauhara field delineated by the resistivity boundary, but open in the west to influence from Wairakei geothermal field. Although the two fields are connected hydrologically, Tauhara is a separate entity because it has its own source of hot upflow. Mount Tauhara and Lake Taupo are significant large scale features in the conceptual model.

The geological cross-sections (Fig) show the existence of surface aquifer(s), a relatively impermeable caprock structure (the Huka layer) and the main geothermal aquifer (the Waiora formation) which extends from 0 mASL downwards. The surface formations follow the line of the land and slope gently downwards to the lake and river where they eventually pinch out.

Somewhere deep down there is a source of hot fluid. The exact location and magnitude of this upflow is not known, but a consistent estimate will be obtained in the course of the model development.

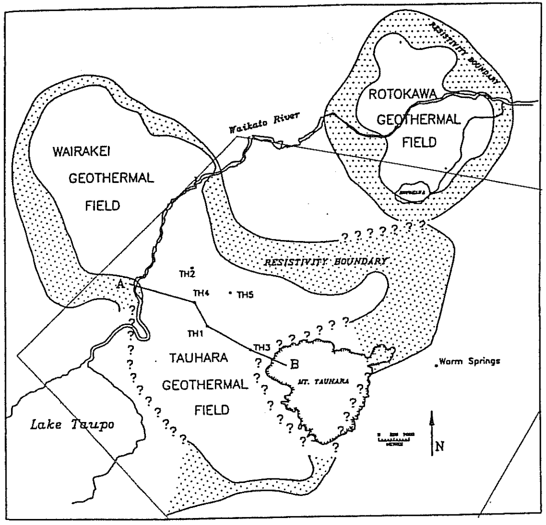

Figure 4: Location of the Tauhara geothermal reservoir and outline of area modeled.

Figure 5 : Geological cross-section of the field

4.1 The Numerical Model

Figure 4 shows the outline of the model superimposed on a map. The model extends beyond the resistivity boundary except in the west where there is a separator across the neck which unites Tauhara with Wairakei. The total area covered by the model is about 195 km^2, and the part within the resistivity boundary about 60 km^2.

The presence of the separator implies that we are modelling Tauhara geothermal field as the principal object, rather than the combined Wairakei-Tauhara system. The influence of Wairakei is still included in the model, but only as a boundary condition.

Vertically the model extends from 1000 mASL down 2.5 km to 1500 mBSL. The topmost level AQ includes the top of Tauhara mountain, Lake Taupo is at level AM, and the Waiora aquifer extends downwards from level AH (0 mASL).

The model has a total of 17 horizontal layers and 1147 elements.

Material properties For each block of the model a rock type is defined following the indications of the conceptual model.

Boundary Conditions The model is open along its boundaries except along the separator (the Wairakei-Tauhara link to be discussed shortly). This allows fluid flow between the area covered by the model and the surrounding countryside, but the low permeability limits the size of these flows. It is believed that the catchment area for the field is larger than the area modelled, and this device keeps the model of a manageable size without detracting from its realism.

The hot upflow is treated as a source of hot fluid at the base of the model. Note that only part of the upflow will reach the surface: the remainder flows out into Lake Taupo or through the other boundaries of the model. The distribution and magnitude of the source will be obtained as part of the modelling process.

The surface boundary condition over the land is air at 1 bar and 15° C, while for Lake Taupo it is water at this pressure and temperature. The air boundary condition means that we can effectively model the vadose zone above the water table and better represent surface heat flows. Rainfall is included in the model by injecting water into the surface elements at an appropriate rate. Hot springs are represented as pressure dependent fluid sinks.

The connection with Wairakei. In the natural state (pre-1957) there is no special connection other than the natural outflow across the separator boundary. During the period 1957-1977 pressures at Tauhara fell by 18 bars. There has never been production from Tauhara itself, so the pressure drawdown must be associated with the exploitation of the Wairakei field (where pressures fell by 26 bars during the same period). The impact of Wairakei production on Tauhara is represented in the model by including a series of sinks along the separator boundary. To ensure that these sinks draw on the hot water inside the model and not on the cold water outside, this boundary is closed between levels AA and AK (-1500m to +300m ASL). Above level AK the separator boundary is open, but it should be emphasised that the "real'" Wairakei-Tauhara connection is *at depth*, represented in the model by the production sinks. The strength of these sinks is adjusted as part of the calibration procedure to give the observed pressure drawdown in the Tauhara aquifer.

4.2 Data and Calibration

Compared with Wairakei there is relatively little data about conditions in the Tauhara field. During the period of investigation there were 3 monitor wells (TH1-3) penetrating the geothermal aquifer. Downhole pressure and temperature profiles from these wells constitute the bulk of the observations. In addition 3 surface heatflow surveys were completed, and later, a repeat gravity survey. Data from several resistivity surveys delineated the field with increasing accuracy.

This information has been incorporated into the numerical model by adjusting material (and other) parameters until model predictions and field measurements were in approximate agreement. The ITOUGH2 program has been largely instrumental in reaching an excellent fit between observation and model predictions.

The steady state. Important adjustable parameters in the model were: (1) the strength of the hot upflow (must exceed the surface heatflow); (2) vertical permeabilities in the various strata; (3) horizontal boundary permeabilities (controls steady state mixing with cold water). The observations were: (1) (inferred) downhole P and T profiles; (2) surface heat flow in the steady state, estimated at 150 MW (Gregg, 1958), later reduced to 107 MW (Fisher, 1965).

Beginning with a ``reasonable" choice of material parameters, ITOUGH2 was run in steady state mode until the average relative error SS (eqn (1)) was minimised. The result was a good fit of model P and T profiles to measured (inferred) values (Figs). In addition the magnitude of the hot upflow of 300^{0} C fluid at the base of the model could be estimated. The thermal energy carried by this fluid was calculated to be 280 MW. Of this, about 100 MW reached the surface in good agreement with observation, the remainder was transported into Lake Taupo or through the other lateral boundaries in the model.

Wairakei production. During the period 1957-1977 Tauhara reacted strongly to fluid extraction from Wairakei. As already noted reservoir pressures fell by 18 bars, and a considerable fraction (unknown) of the hot upflow at Tauhara was diverted to Wairakei. In addition there was a dramatic increase in surface heat flow, from 107 MW (pre-1955) to 220 MW by 1972 (Dickinson 1972, 1975). Even larger heat flows were inferred after 1972 (Mongillo 1989), though these have been disputed. More recently surface heat flows are thought to have declined.

Major adjustable parameters in the model during this phase are: (1) the strength of the sinks along the separator boundary representing Wairakei production; (2) horizontal permeability in the geothermal aquifer (Waiora formation). The observations consist of time-varying downhole P/T profiles and the changing surface heat flows.

Beginning with the natural-state configuration ITOUGH2 was run until the average relative error SS was minimised. This implied a change in the Waiora permeability. The steady-state iteration was run again with this new value. The whole cycle was repeated several times. The final best fit had roughly 50\% of Wairakei production coming from Tauhara, implying an extremely good connection between the two fields. This fluid can be thought of as diverted from the original hot upflow at Tauhara, though there is, in addition, a hot recharge stimulated by the pressure drawdown. Tauhara fluid has a specific chemical signature, but so far no Tauhara component has been identified at Wairakei. This is to be expected since simple calculations suggest that chemical breakthrough is only just now occurring. In another 10 years it should be clearer whether the model predictions concerning the magnitude of the cross-flow are of the right order.

Good agreement was obtained between the time-varying model pressures and temperatures, and field values (Figure 6). In the model a steam zone formed in the geothermal aquifer (in response to Wairakei production) which agrees with the results of the micro-gravity surveys. The observed surface heat pulse was duplicated in the model (Figure 7). The model shows an increase in surface heat flow from just over 100 MW in 1957 to 170 MW in 1967. Heat flow then decreases slightly before increasing slowly to about 200 MW in 1980. The model surface heat flows agree quite well with field estimates in the early stages, but the model does not predict a decline in surface heat flow until after the year 2000.

Summary. Overall the Tauhara model -- incorporating the parameter refinements suggested by ITOUGH2 -- has been very successful. It has been used in water rights applications and to run various production scenarios for the future development of the field. The importance of the air boundary condition should also be emphasised. Without this another model predicted large mass (and energy) *downflows* at Tauhara in response to Wairakei production, rather than the surface heat pulse which was actually observed.

5. Conclusions

We learnt a number of lessons from the Kawerau exercise using ITOUGH2, perhaps the most important were

1. start with a *small* simple model
2. vary only sensitive parameters
3. use the fastest computer you can find
4. it is easier to match time varying data than steady state data.

Also, most importantly, ITOUGH2 cannot work miracles. To obtain good estimates of model parameters you must have data that is sensitive to those parameters. Obviously this is true of any method used to fit parameters but is perhaps ignored when error estimates of fitted parameters are not available.

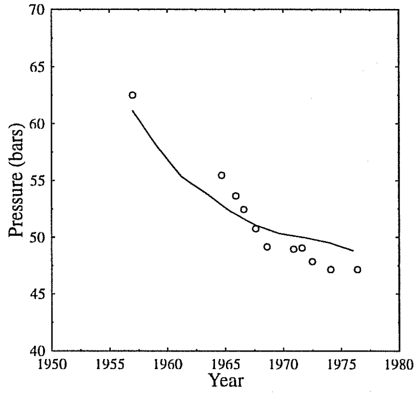

Figure 6: Match to pressure drawdown at well TH1

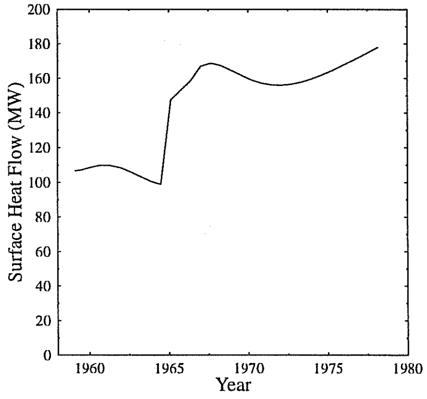

Figure 7: Change in surface heat flows in response to Wairakei production.

For the work on Tauhara we obtained very good results using ITOUGH2. The most positive aspects were the great savings in time and the good match obtained to measured data.

6. References

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