Geothermal Resources Council Transactions, Vol. 24, September 24-27, 2000

Two-Dimensional Modeling of the Tauhara Geothermal Field

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ABSTRACT

The Tauhara geothermal field is located within the Taupo Volcanic Zone (TVZ) of New Zealand and is in direct hydrological communication with the Wairakei geothermal field, which has been producing for over 40 years. Production from Wairakei has caused 15 to 18 bar decline in deep reservoir pressures at Tauhara, steam formation in shallow aquifers and secondary effects of ground subsidence, changes in surface thermal activity and hydrothermal eruptions. A two-dimensional numerical simulation model was constructed to match the historical changes in deep reservoir pressures at Tauhara and the associated changes in heat flow and water saturation in the shallow aquifers. The model was also used to investigate the changes that might occur, particularly to the shallow steam-dominated zones, as a consequence of direct development of the Tauhara field. The results suggest that the incremental impact of direct Tauhara development would be small as the major changes have already taken place. The results also indicate that selective injection of 160°C separated brine and 20°C condensate to shallow and intermediate aquifers may reduce steam zone formation while maintaining pressure, thereby mitigating the effects of steam heating on the shallow formations and the risk of further subsidence. However, care would need to be taken with placement of injection to avoid detrimental effects on the users of the numerous shallow bores in the area.

Introduction

The Tauhara and adjacent Wairakei geothermal fields are located in the Taupo Volcanic Zone (TVZ) of New Zealand, close to the northern end of Lake Taupo (Figure 1) where the Tauhara field partially underlies the Taupo township. The Wairakei field presently has an installed capacity of 161 MWe and has been exploited on a continuous basis for electrical generation for over 40 years while the Tauhara resource has only been utilised for domestic heating and commercial processing. Although the two fields have separate heat sources, they are hydrologically connected, as evidenced by changes that have occurred in both the reservoir and surface features at Tauhara in response to Wairakei production. These changes have included decline in reservoir pressure, land subsidence, changes in the nature and location of surface thermal activity and hydrothermal eruptions (Scott and Cody, 1982).

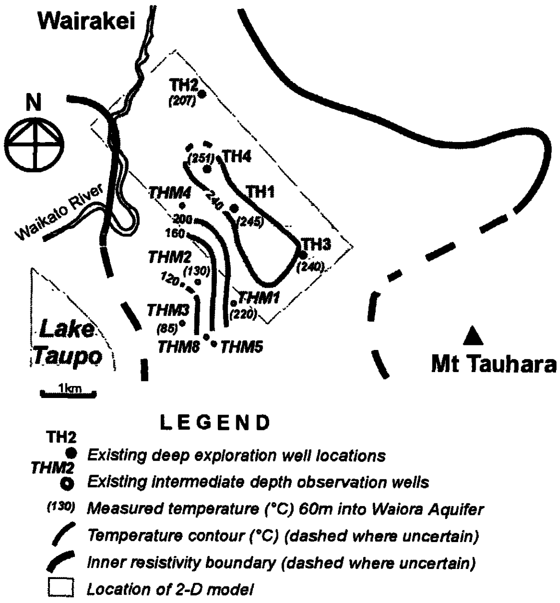


Figure 1. Location Map, Tauhara Geothermal Field.

In 1995-96, three developers put forward proposals to utilise the Tauhara resource for electricity generation. As part of the permitting process, the developers were required to investigate the possible effects that development would have on the environment. Based on the historical changes, the major concerns included further land subsidence and the possibility of hydrothermal eruptions, particularly as some of the area overlying or close to the Tauhara field is now populated.

The historical changes in surface activity at Tauhara are associated with the formation of a shallow steam zone, formed in response to decline in deep reservoir pressures. A numerical modelling study was therefore undertaken to investigate the effect of direct development of Tauhara on the deep reservoir and existing steam-dominated conditions in the shallow aquifers. A number of scenarios were considered, including the use of selective injection to mitigate steam formation and maintain pressure. The numerical model was constructed using TOUGH2 (Pruess, 1991), a numerical simulation package developed at Lawrence Berkeley National Laboratory, Berkeley, California for modelling geothermal systems.

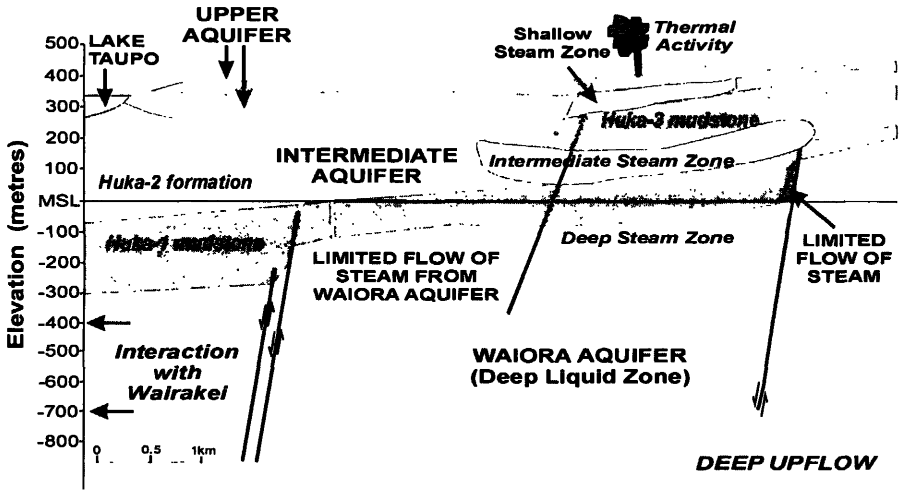


Figure 2. Cross Section of the Tauhara Geothermal Field.

Model Development

For the Tauhara field, there is a significant historical database available from which to develop both conceptual and numerical models. A number of wells have also been drilled in the field and details regarding the geology, geochemistry and reservoir properties of the Tauhara resource have previously been published (see Bibliography).

Geology and Hydrology

The Tauhara reservoir is essentially a "layer-cake" pile of formations with distinct variations in vertical permeability, but with well-distributed horizontal permeability (Figure 2). The formations include silicic volcaniclastic and epiclastic-lacustrine formations of Holocene-Recent age. They are crosscut by recent faults, but in contrast to Wairakei the influence of faulting on permeability does not appear to be as significant.

Three major aquifers have been identified at Tauhara (Figure 2):

Σ The deepest aquifer is located within the Waiora Formation, and is referred to as the "Waiora Aquifer". It is present at both Wairakei and Tauhara and provides the main hydrological connection between the fields.

Σ The "Intermediate Aquifer" is located in the Huka 2 formation. It is isolated from the Waiora aquifer by the Huka 1 mudstones and confined from above by the Huka 3 mudstones. The aquifer may be in hydrological connection with Lake Taupo as water levels are similar. Some wells tap this aquifer for direct use, though the total withdrawal is small.

Σ A "Shallow Aquifer", which occurs above the Huka 3 mudstones. Less permeable formations within this aquifer may locally divide it into two separate aquifers. Numerous shallow wells tap this aquifer for direct use.

Pressure Distribution and Drawdown

The initial pressure profiles in both the Tauhara and Wairakei geothermal fields (prior to exploitation of Wairakei) were probably similar, due to the good hydrological connection between the two fields through the deep Waiora aquifer. This means that prior to Wairakei production, the fluid in the Waiora aquifer was almost entirely single phase liquid (Allis, 1983).

Wairakei production has resulted in pressure drawdown of approximately 25 bar at Wairakei, with most of the drawdown occurring between 1958 and 1970 (Figure 3). Since 1970, the rate of pressure decline has decreased significantly and deep liquid pressures have remained reasonably constant since the mid to late 1980's. In the deep Waiora aquifer at Tauhara, data from wells TH-1 to TH-4 suggest that pressure decline has followed the Wairakei trend, with the total drawdown estimated to be between 15 to 18 bar (Figure 3). The deep pressure drawdown has caused the formation or enlargement of two-phase zones at the top of the Waiora aquifer and in the Intermediate aquifer. This has led to steam heating of the shallow aquifers, with an increase in the size and intensity of steaming ground and heating of some hot springs. The steam heating is also believed to have triggered three hydrothermal eruptions in the Tauhara area.

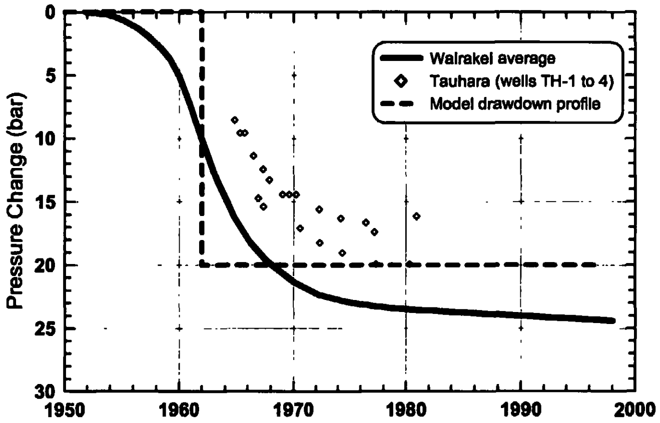


Figure 3. Pressure Changes at Wairakei/Tauhara.

With the change in pressure gradient between the two fields, Tauhara has also now become a significant "recharge" source for Wairakei, providing between 250 kg/s (DSIR, 1988) and 400 kg/s (Youngman, 1984) of fluid.

Temperature Distribution

Based on measured downhole temperature data, it is apparent that the upflow for the Tauhara geothermal field is separate from Wairakei and occurs in the TH-3/Mount Tauhara area (Figure 1); the maximum downhole temperature measured within the Tauhara field is approximately 280°C, in well TH-3. Although deep temperature data are limited, the sub-surface temperature distribution appears to be elongated along a NW-SE axis from Mt. Tauhara towards Wairakei (Figure 1).

Description of the Numerical Model

The numerical model consists of a two-dimensional cross section or "slice" through the Tauhara field, orientated along the main axis of the deep temperature anomaly (Figure 4). The cross-section is 5km long, with a width of 2km, which defines the extent of the main high temperature anomaly. With the 2-D model, it was possible to obtain a reasonable representation of the field's complex geologic structure although there are limitations, particularly with regard to addressing resource sustainability issues or providing information on the actual location of future surface activity. These issues would need to be addressed using a more complex three-dimensional model of the Wairakei/Tauhara system.

The basic model layout (Figure 4) is similar to the conceptual cross section shown in Figure 2. The model is divided into ten, 500m grid block columns, split into 13 layers of varying thickness and extending from ground level, which is between 400masl (above sea level) and 420masl to a total depth of -770masl. The relatively large number of layers is required to account for the various geological units in the Tauhara field and to improve the accuracy of modelling two-phase conditions. Where two-phase conditions occur, a larger number of "thin" layers is required to adequately represent the steam saturation gradients. However, where single-phase conditions are present, thicker layers can be used.

The basic boundary conditions used in the model (Figure 4) include:

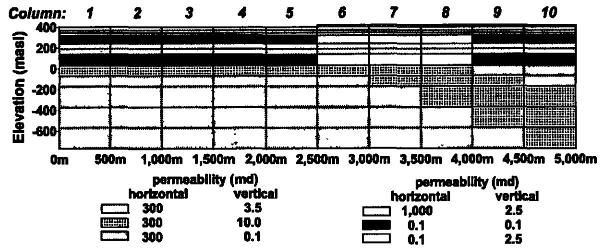
- Σ Closed sides and base except at specific locations where inflows or outflows are defined. "Constant pressure" blocks are used to control the sub-surface inflows and outflows during the initial state modelling.
- Σ An "atmospheric" block connected to the top layer to act as a conductive heat sink.
- Σ Two pressure dependent outflows defined in the top layer to simulate hot spring discharges.

For modelling the flow of steam and water between blocks, relative permeability curves based on Grant (1977) were used, with the immobile steam and water saturation's defined as 0.00 and 0.30, respectively.

Initial State Modelling Results

The required match to initial state conditions was obtained using the permeability distribution shown in Figure 4. In the aquifers, relatively high horizontal permeability's (300 and 1,000 md) were used while a very low horizontal permeability of 0.1 md was used in the intervening mudstone formations. Greater variation was required in the vertical permeability distribution, however, to control the calculated temperature distribution. In the Waiora aquifer, a vertical permeability of 0.1 md was used in most of the grid blocks, with 10 md used where upflow was required. A low vertical permeability (0.1 md) was also used to model the Huka 1 and Huka 3 mudstones, except in localised areas where a vertical permeability of 2.5 md was used to allow fluid flow to the shallow aquifers and surface.

a) Grid Block Permeabilities



b) Boundary Conditions

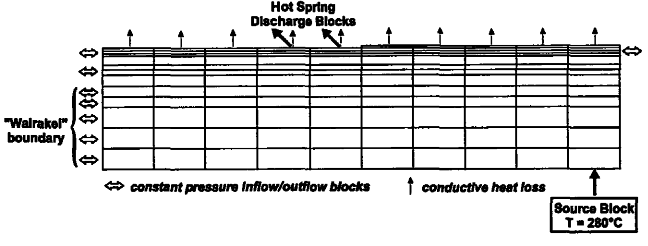
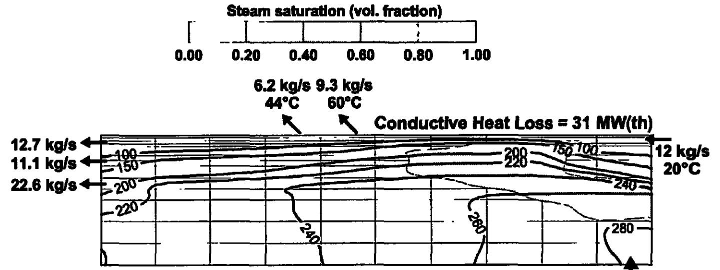
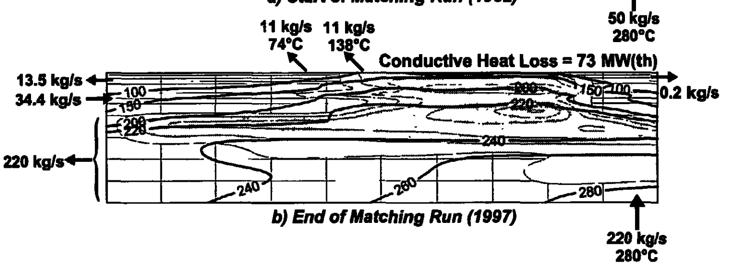


Figure 4. Two-Dimensional Simulation Model Properties.



a) Start of Matching Run (1962)



b) End of Matching Run (1997)

Figure 5. Initial State Modeling/History Matching Results.

The calculated temperature contours (Figure 5) and profiles (Figure 6) through the model are in reasonable agreement with available measured data. The temperatures in the shallow system are significantly hotter above the blocks with higher vertical permeability (column 8) due to the flow of hot fluid to the intermediate and shallow aquifers. Away from these blocks, such as in column 1, the shallow profile indicates conductive rather than convective conditions.

Figure 5 indicates that under natural state conditions there is some steam formation in the reservoir, both above the upflow zone and within the intermediate aquifer. However, the amount of steam is small (steam saturation < 0.2) and does not have a significant impact on the calculated pressure gradient (Figure 6), which is consistent with the natural state pressure profile defined by Allis (1983).

The overall mass and heat flows calculated by the model do not necessarily agree with measured data due to the 2-D nature of the model. However, the calculated temperatures of 44°C and 60°C for the "hot spring outflows" are in good agreement with measured temperatures from the local springs prior to production from Wairakei (Bromley and Glover, 1996; for example the A.C. (42°C) and Kathleen (62°C) hot springs).

Matching Response to Wairakei Production

The impact of Wairakei production was simulated by connecting "constant pressure" boundary blocks to the "Wairakei" boundary (Figure 4), with a defined pressure 20 bar below the natural state model pressures. This imposed a step change in pressure, which is a reasonable approximation to actual conditions as the majority of the pressure decline occurred over a relatively short period of time (Figure 3). The step change is imposed in 1962 and the model was run for 35 years to simulate the changes in the field from 1962 through to 1997.

For the history matching and forecast runs, the inflow of 280°C water to the model was controlled by a series of concentric, radial grid blocks of increasing but finite size. The blocks were sized to maintain the pressure drawdown in the model at 15 to 18 bar, corresponding to the actual level of drawdown measured in the deep Tauhara wells, TH-1 to TH-4 (Figure 3).

The applied pressure drawdown of 15 to 18 bar initially caused expansion of the two-phase zone at the top of the Waiora aquifer. With increasing time, steam saturation increased and the two-phase region expanded into the intermediate and shallow aquifers. After 35 years, the two-phase zone is extensive, with steam saturation exceeding 0.7 in the fluid upflow through the low permeability confining layers. Note that the steam saturation of 0.7 corresponds to the specified "residual" water saturation of 0.3; where this is exceeded, the water becomes immobile and only steam is able to flow between blocks. Hence, these blocks have become "steam-dominated".

The calculated pressure profiles (Figure 6) in columns 1 and 8 show that although pressures in the deep Waiora aquifer fall by 15 to 18 bar, the pressures in the upper aquifers initially rise due to the formation of lower density two-phase fluid conditions between –300masl and +100masl. With increasing time, however, the pressure decline in the Waiora aquifer overcomes the density effect and shallow pressures then start to fall.

The pressure changes in the two-phase region are accompanied by corresponding changes in temperature. In column 8 (Figure 6), there is an initial rise in temperature in the shallow aquifers (above sea level) followed by a fall, while a significant decline in temperature occurs between sea level and –400masl.

Although shallow pressures initially rise in the model, available measured data suggest that water levels in the shallow aquifers have remained relatively constant with time. This may be due to the effects of rainfall, influence of Lake Taupo or other near surface conditions that are not included in the model. However, the hydrothermal eruptions and other changes to surface activity that have occurred at Tauhara certainly indicate that shallow pressures and temperatures did rise, at least locally, as a result of steam formation.

Changes also occurred to the inflow and outflow blocks (Figure 5). The shallow inflow block became an outflow block after approximately 5 years of production due to the initial rise in pressure. A reversal of flow also occurs in the intermediate aquifer, where the outflow block becomes an inflow block after approximately 15 years. The outflow through the "Wairakei" boundary reaches 220kg/s by the end of the matching run, which is close to the range of estimated recharge (250 to 400kg/s) from Tauhara to Wairakei.

For the two "hot spring outflow" sinks, temperatures increase with time, which is generally consistent with trends measured in the various springs in the area (Allis, 1983 and Bromley and Glover, 1996). However, the maximum calculated temperature of 138°C is greater than measured temperatures as it reflects temperatures within the first layer of the model rather than at the surface. The measured spring temperatures do not exceed 100°C due to atmospheric boiling and the influence of rainfall, which are not taken into account in the model. The overall flow from the two hot spring discharges calculated by the model (22 kg/s) is, however, reasonably consistent with measured spring discharge rates.

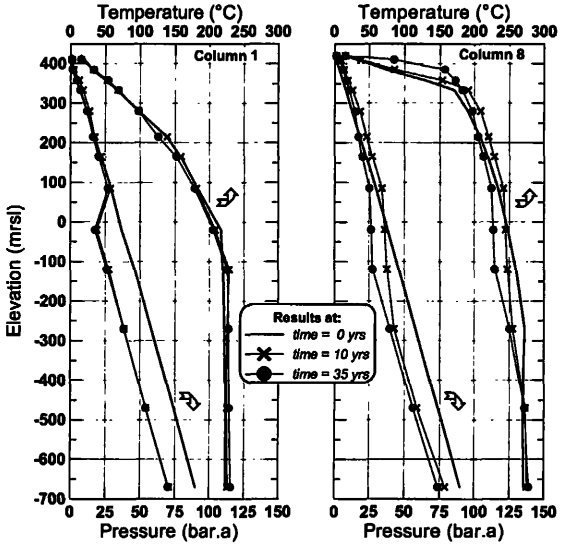


Figure 6. Model Temperature and Pressure Profiles.

The heat flow from the top of the model more than doubled during the 35 year simulation period, from an initial value of 31MW(thermal) to a final value of 73MW(thermal). This is associated with the change in near surface fluid conditions from liquid to steam dominated, which is consistent with the observed behaviour.

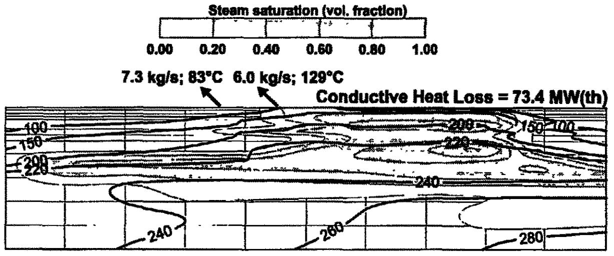
Future Changes Due to Tauhara Development

A number of scenarios were run to investigate the impact of additional deep pressure decline on fluid conditions within the reservoir and how injection could be used to control steam formation and maintain pressures in the shallow and intermediate aquifers. However, with the inherent limitations of a 2-D model, the scenarios are relatively simple and the results are considered to be indicative only. More extensive 3-D modelling would be required to fully characterise the impact of production and the various injection options, particularly with respect to the specific areas of the reservoir that would be affected.

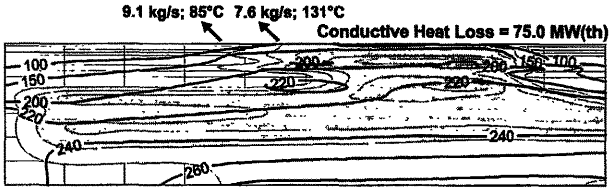
The initial scenario, Scenario 1, was based on maintaining the status quo, while in Scenario 2, the imposed drawdown in the Waiora aquifer was increased to reflect additional development. Scenarios 3 and 4 considered partial injection of 160°C separated water and 20°C condensate at shallow and intermediate levels to control steam formation and maintain pressure.

Contour plots of temperature and steam saturation after 25 years production for each scenario are presented in Figure 7 (a to d). The calculated mass flows and temperatures for the two surface spring discharges and the overall conductive heat loss are also shown.

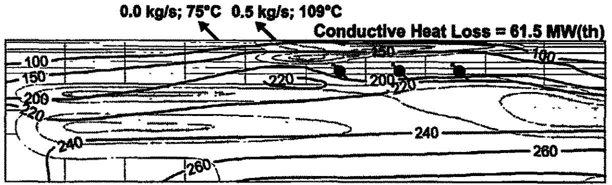
With Scenario 1, there is continued evolution in reservoir conditions with time, including a continuing but small reduction in pressure and a corresponding reduction in temperature within the two-phase zone. Steam saturation does not change significantly in the deep aquifer but there is an increase in steam saturation (up to 0.9) where steam is able to migrate from the deep aquifer into the intermediate and shallow aquifers. In terms of the spring discharges, flow rates decline with time but there is an increase in temperature in one of the simulated spring discharges from 74°C to 83°C; in the other, the temperature decreases from 138°C to 129°C. The conductive heat loss remains relatively constant over the simulation period.



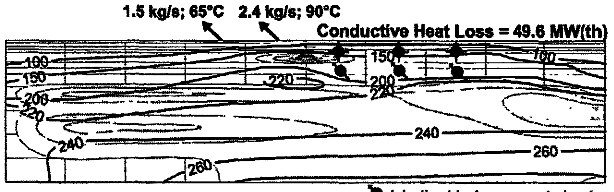
a) Scenario 1



b) Scenario 2



c) Scenario 3 injection blocks - separated water



d) Scenario 4 injection blocks - separated water
injection blocks - condensate

Figure 7. Forecast Run Results (25 years).

For Scenario 2, the additional imposed drawdown in the Waiora aquifer causes a significant enlargement of the two-phase zone within the deeper layers of the model; after 25 years, most of the Waiora aquifer is two-phase, with steam saturation of up to 0.4. The lower pressures and the formation of two-phase conditions also result in a reduction in deep temperatures. In the shallow two-phase zones, the thermodynamic conditions do not change significantly when compared to the results for Scenario 1, although there is a slight increase in pressure due to the expansion of the two-phase zone. The changes in spring discharges are similar to Scenario 1 and there is little or no increase in conductive heat loss. Hence, the results suggest that development of the deep resource at Tauhara should have little or no additional impact on the surface and near surface thermodynamic conditions when compared to maintaining the status quo. This is consistent with Grant (1985), where it is stated: *"once the steam zone exists, the surface layers are not directly coupled to the deep reservoir and exploitation does not affect them directly. Changes can still occur but only through the intermediary of the steam zone. The major surge in surface steam discharge is a one-time event associated with the creation of the steam zone".*

The major effects of injection (Scenarios 3 and 4) are localised within the shallow layers, where steam saturation is reduced significantly by the injection of cooler water. This reduces the spring temperatures and also the conductive heat loss. The reduction in shallow pressures, due to changes in fluid density, also reduces the spring flow rates over the simulation time and after 25 years there is little or no flow from the spring outflows when only considering injection into the intermediate aquifer. With injection of condensate in the shallow aquifer, pressures are better maintained so that the springs continue to flow, although temperatures are reduced due to the change to liquid dominated conditions. There is also no sign of significant temperature decline in the deep aquifer even though some of the injected water flows into the deeper aquifer.

Conclusions

1. The two-dimensional model of the Tauhara geothermal field has provided reasonable matches to both the initial state and to the generic changes that have occurred in the field as a consequence of Wairakei production.
2. The model shows that at the present time, two-phase conditions exist at the top of the deep Waiora aquifer and in the intermediate and shallow aquifers. The maximum steam saturation of 0.7 occurs within the blocks where fluid migrates from the deep aquifer into the intermediate and shallow aquifers.
3. Development of the deep Tauhara resource should not cause significant additional changes to the surface aquifers or to the thermal manifestations when compared with maintaining the status quo.
4. Selective injection of separated water and/or condensate to the shallow and intermediate aquifers may provide a viable method of controlling excessive build-up of steam in the shallow system and for maintaining pressures, should this be necessary. This will mitigate problems associated with steam heating of the shallow formations and reduce the risk of further subsidence.

Acknowledgement

The permission of Mercury Geotherm Limited to publish this paper is gratefully acknowledged.

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