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# REINJECTION INTO LIQUID-DOMINATED TWO-PHASE GEOTHERMAL SYSTEMS

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## ABSTRACT

A 3D numerical model of the Wairakei-Tauhara field is used to investigate the effect of reinjection on liquid-dominated two-phase geothermal systems. Wairakei-Tauhara is an interesting case study as it has been operated with no reinjection for most of its lifetime. Several scenarios are run with the model to test what would have happened if different reinjection strategies had been followed. The impacts of different rates of outfield and infield reinjection on production enthalpy, reservoir pressure and temperature, recharge conditions and surface features are investigated.

Our modelling results show that infield reinjection has two negative effects on energy production. The first and major effect is that infield reinjection suppresses boiling and therefore decreases the average production enthalpy. Secondly as reservoir pressures are maintained by infield reinjection, deep hot water recharge to the system is suppressed and replaced by the much colder injected fluid. These two effects are small for low levels of infield reinjection (up to 25% of the separated water) and therefore this appears to be a good infield reinjection strategy.

Reinjection has an important effect on surface features. With no reinjection the large pressure drop caused by production results in a decrease over time in the flow of chloride water from the deep aquifers to the surface features. Also with no reinjection shallow boiling zones may develop in some areas, and cause the ground surface above to become steam heated. Reinjection supports the flow of chloride water to the surface features, but at a lower temperature than in the natural state. However if the reinjection zone is close to the steam-heated surface features they may significantly decline or totally disappear.

## INTRODUCTION

Liquid dominated two-phase geothermal systems contain all, or mostly, very hot water in their natural state. However, when production commences, boiling occurs near the production wells, caused by large pressure drops. The permeability in some of the rock surrounding the hot reservoir in such systems may be similar to that inside the reservoir. Therefore recharge from the sides of the reservoir can easily take place. In the Wairakei-Tauhara geothermal system permeabilities are high. There are a number of NE–SW trending faults that provide enhanced permeability in the field (Mannington *et al.* (2004), Chapter 2 in Rosenberg et al. (2010)). Hence there is substantial recharge that provides natural pressure support to the system (Bixley *et al.* (2009)).

In liquid-dominated two-phase systems, injecting cold water into the production zone will cause faster cooling of the production wells. In some cases, it may even suppress boiling and cause the production enthalpy to drop to that of hot water. Systems of this type do not run out of water, and also they do not suffer from excessive pressure drawdown because the pressure declines until it reaches the boiling point and then the boiling process "buffers" any further decline. Thus this type of system does not require pressure maintenance, and from a reservoir engineering perspective there are no reasons for injecting infield in two-phase liquid-dominated geothermal systems.

Past experience shows that injection in such systems has often resulted in adverse thermal breakthrough and a consequent move of injection outfield, e.g. at Cerro Prieto (Lippmann *et al.* (2004)) and Tiwi (Sugiaman *et al.* (2004)).

At Wairakei, production has caused widespread pressure drawdown. The drawdown has stabilized at approximately 25 bar in the deep liquid zone of the Wairakei field. The large pressure drawdown has caused the formation of extensive two-phase zones (Bixley *et al.* (2009), Mannington *et al.* (2004), Chapter 5 of Rosenberg *et al.* (2010)), and a shallow vapour-dominated zone has formed in a predominantly low-enthalpy, liquid-dominated system.

The large pressure drop in the reservoir has caused a reduction in surface flows at liquid-fed features (geysers and hot springs) and an increased heat flow, mainly from steam, through the surface at some locations. For example in the pre-exploitation state of the Wairakei-Tauhara geothermal system there was a large chloride water up-flow from the deep reservoir that mixed with groundwater, and discharged to the surface, mainly at Geyser Valley (Bromley (2008), Chapter 8 of Rosenberg *et al.* (2010)). As a result of production the vertical pressure gradient in shallow parts of the reservoir decreased and thus lowered the up-flow from the deeper high-temperature reservoir.

A large area of steam discharge was present at the Karapiti thermal area even before production started. After production commenced, because of the pressure drop in the reservoir and expansion of the boiling zone, the steam flow to the surface increased. Now the area contains hot ground, numerous fumaroles and steaming craters (Glover *et al.* (2001), Hunt *et al.* (2009)).

In the Wairakei-Tauhara geothermal field reinjection has been carried out only over the last 10 years. Before that there was no reinjection (Bixley *et al.* (2009)). Thus experiences from this field allow us to observe some of the effect of reinjection on the production performance and field characteristics as well as allowing us to observe the results of production without reinjection.

## MODEL DESCRIPTION

An existing computer model of the Wairakei-Tauhara field (O'Sullivan and Yeh (2007)) is used. The areal and vertical grid structures of the model are shown in Figure 1. The top few layers of the model follow the topography of the Wairakei-Tauhara region.

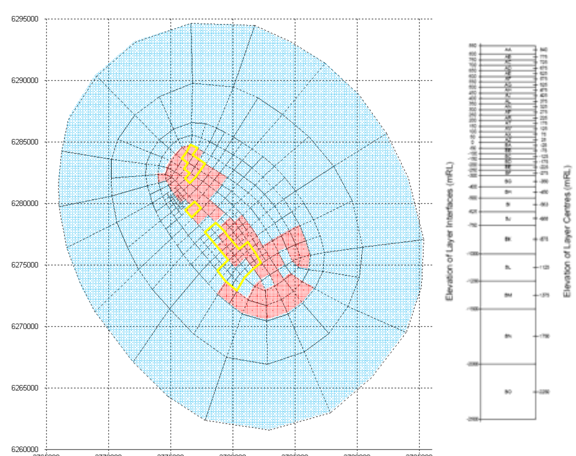



*Figure 1. Areal and vertical structure of the Wairakei–Tauhara model*

In order to obtain an accurate representation of the shallow zone, the unsaturated zone is included in the model and thus the model considers the flow of energy, water and air within the geothermal system (O'Sullivan *et al.* (2001), Mannington *et al.* (2000)).

### Natural State Model

Pre-exploitation conditions of the Wairakei-Tauhara system are simulated in the natural state model. Atmospheric conditions are maintained at the ground surface with 1 bar pressure and 15°C temperature. To implement the infiltration of rainwater, a proportion of the average rainfall is injected into the surface blocks at a temperature of 15°C. To represent the lake at the south west of the system, a wet atmosphere and a cold temperature (5°C) is assigned to the blocks representing the lake area.

At the base of the model, mass inputs (red area in Figure 1) and heat inputs (blue area in Figure 1) are applied as boundary conditions.

A cap-rock is located in the AP layer (+275masl) and nearby. Surface outflows to hot springs (the grid-blocks bounded with yellow lines in Figure 1) are represented in the model by mass flows from beneath the cap rock.

The Wairakei geothermal reservoir is characterised by high horizontal permeabilities, but there are low permeabilities in the basement and cap-rock (Mannington *et al.* (2004), O'Sullivan and Yeh (2007), O'Sullivan and Yeh (2010)).

To improve the fit of the natural state model results to the field data, calibration has been carried out over many years. Simulation results are compared with pre-production measurements (e.g. reservoir temperatures, surface outflow locations and vapour saturations). The main parameters adjusted are the permeabilities and the deep inflows (Mannington *et al.* (2004), O'Sullivan and Yeh (2007), O'Sullivan and Yeh (2010)).

### Production history

The historical data for production and reinjection at the Wairakei field are used as input in the simulation of the production history. The initial conditions for the production history model are taken from the natural state model. Further calibration has been carried out to obtain a match of the model behaviour to the measured changes in pressures, production enthalpies, surface heat flows, temperatures and vapour saturations (Mannington *et al.* (2004), O'Sullivan and Yeh (2007), O'Sullivan and Yeh (2010)).

The production wells are grouped according to their locations in one of four production areas: Eastern Borefield, Western Borefield, Te Mihi and Poihipi.

Almost all of the production at Wairakei has been taken from between +100masl to -500masl. The major part of the production has been from the Western Borefield, but at a decreasing mass flow rate throughout the past 40 years as production from Te Mihi has increased. The total production from the Eastern Borefield area has decreased gradually and this area has produced only about 30kg/s for the last 15 years.

**REINJECTION EXPERIENCE AT WAIRAKEI-TAUHARA**

In the Wairakei-Tauhara field for the first 40 years of production (up to ~1995), the bulk of the cooled geothermal fluid (both condensed steam from the direct-contact condensers and the separated brine) was discharged into the Waikato River, as shown in Figure 2 (Bixley *et al.* (2009), Chapter 5 of Rosenberg *et al.* (2010)). After 40 years of production, a small amount of the separated geothermal water was reinjected close to the Eastern Borefield.

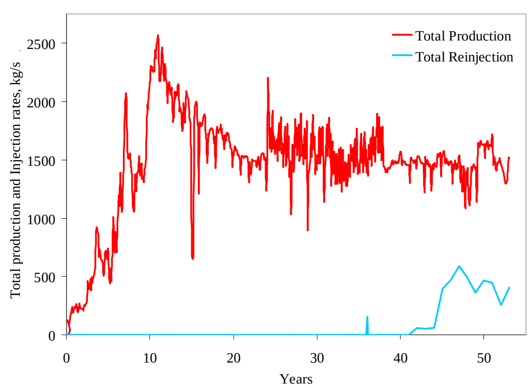



*Figure 2. Production and injection history for Wairakei.*

As a result of this strategy of no reinjection for forty years followed by a small amount of reinjection for ten years, the following effects have been observed:

(a) A large two-phase zone, with a high vapour saturation in some locations (steam zones), has formed and the enthalpy of some of the production wells has increased (Mannington *et al.* (2004), Bixley *et al.* (2009), Chapter 5 of Rosenberg *et al.* (2010)).

(b) An increase in steam heated surface features has been observed (Mannington *et al.* (2004), Bixley *et al.* (2009), Chapter 8 of Rosenberg *et al.* (2010)), but most of the surface features that were fed by hot chloride water have disappeared (Lynne (2008), Chapter 8 of Rosenberg *et al.* (2010)).

(c) There has been a large drawdown in the reservoir pressure. This has induced an increase in cool recharge from the top and sides of the reservoir and an increase in deep hot recharge. After 30 years of production, the pressure in the deep liquid zone stabilized at about 25 bar (Mannington *et al.* (2004), Bixley *et al.* (2009), Chapter 5 of Rosenberg *et al.* (2010)).

**REINJECTION SCENARIOS**

In this study our particular interest is to decide if the best reinjection strategy for Wairakei-Tauhara should involve infield reinjection, outfield reinjection or a mixture of both. Therefore alternative reinjection strategies are investigated. The impact of different rates of outfield and infield reinjection on production enthalpy, reservoir pressure and temperature, recharge conditions and surface features is investigated.

The reinjection scenarios examined in this paper are summarized in Table 1. SGW (separated geothermal water) represents the total amount of water produced from the separators. The enthalpy of the reinjected fluid is taken as 564.4kJ/kg corresponding to an average temperature of fluid from the separators of about 134°C.

*Table 1 Reinjection scenarios*

| Scenario | Reinjection Strategy |
|---|---|
| BASE | Historical situation - no reinjection for 40 years, followed by a small amount of reinjection for about the last 10 years |
| OUT | Outfield reinjection of 100% of the total produced mass |
| IN100 | Infield reinjection of 100% of SGW |
| IN50 | Infield reinjection of 50% of SGW |
| IN25 | Infield reinjection of 25% of SGW |

**Outfield reinjection**

The outfield reinjection scenario (OUT) involves reinjecting the waste fluid outside the known reservoir boundaries. It is assumed that the amount of steam loss is negligible and the total mass produced from all of the wells is reinjected.

The locations of the main outfield injection zones were at first based on those used in previous modeling studies of the Wairakei-Tauhara model (O'Sullivan and Yeh (2006)). However the blocks used in the previous study can accept only a limited amount of reinjection and the amount of liquid to be injected for the OUT scenario is large. Therefore we extended the outfield reinjection areas by including large grid blocks next to the reinjection blocks used in O'Sullivan and Yeh (2006). These areas have the largest permeability of all the outfield blocks and thus they have a relatively high injectivity. There are very low permeability regions between the reservoir and some outfield reinjection zones, corresponding to a weak connection to the reservoir. The total mass produced from the different production areas is injected into the outfield reinjection zones in proportion to the volume of these grid-blocks. The depths of the reinjection zones vary between -25masl and -225masl.

A comparison of the pressure and enthalpy histories of the BASE and OUT scenarios shows that outfield reinjection does not affect the pressure behaviour or the thermal state of the reservoir. This is to be expected as there is only a weak hydraulic communication between the outfield reinjection zones and production areas. Hence outfield reinjection can be considered as a waste water disposal method rather than as a technique for maintaining reservoir pressure.

**Infield reinjection**

Infield reinjection involves reinjecting fluid inside the reservoir boundaries and thus into the zones that have a permeable connection with the production areas. Because of the permeability connection between the production and the reinjection zones, the possibility of the rapid movement of cool injected water along preferential flow paths between the injection and production wells is a major concern with infield reinjection.

As can be seen from Table 1, three different scenarios are tried for infield reinjection: IN100, IN50 and IN25 representing injection of 100%, 50% and 25% of the SGW, respectively. The amount of SGW is calculated by subtracting the steam production from the total produced mass. Hence the steam condensate produced from the field is not reinjected.

The total reinjected water is distributed into the infield reinjection grid-blocks in proportion to their volumes.

To decide on the locations of infield reinjection blocks, previous work on the Wairakei-Tauhara model was reviewed. The locations (areal and vertical) for infield reinjection used in previous studies (O'Sullivan and Yeh (2007)), are as shown in Figure 3.

They are convenient areas in the higher permeability regions of the infield zone, located as far as possible from the Wairakei production wells and the future Tauhara production zone.

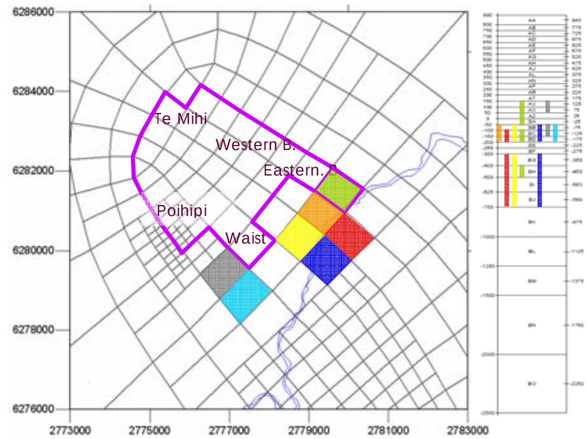
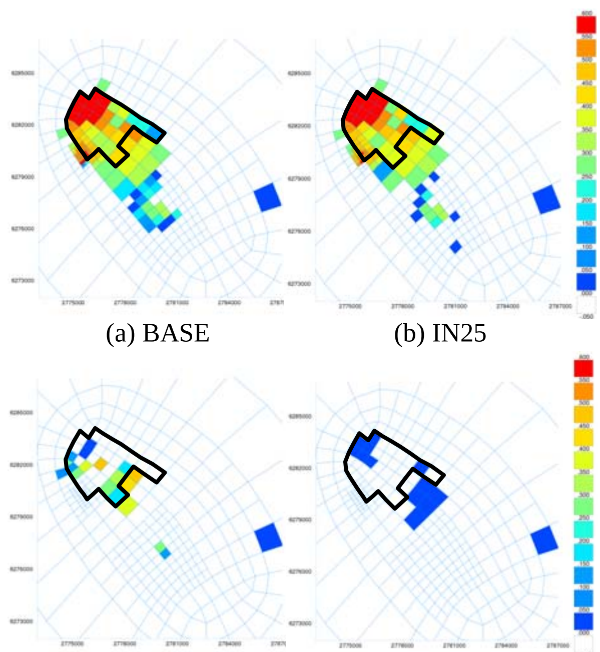



*Figure 3. Areal and vertical location of infield reinjection.*

Since the horizontal and vertical permeabilities are high in the area between the production and infield reinjection zones there is a strong hydraulic connection between them.

The vapour saturations in the AT layer (+175masl) after 53 years of production for the BASE, IN25, IN50 and IN100 scenario are shown in Figure 4a,b,c,d, respectively.



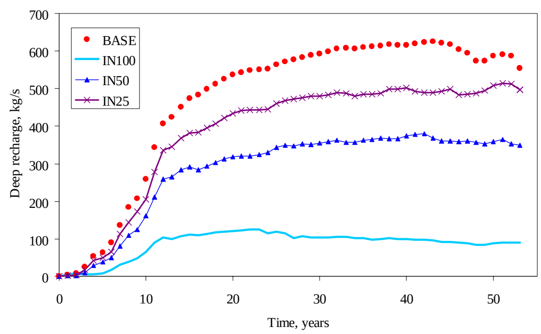
(a) BASE (b) IN25

(c) IN50 (d) IN100

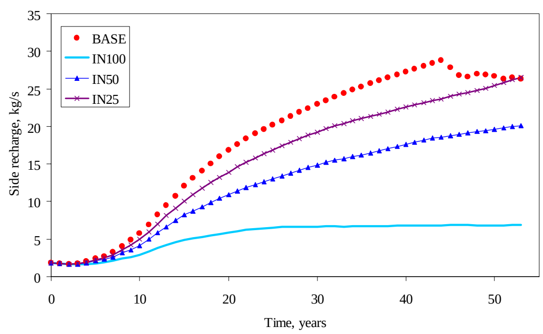
*Figure 4. Vapour saturation distribution in the AT layer at year 53 for: (a) the BASE scenario and (b) the IN100 scenario.*

Comparison of the BASE scenario results (Figure 4a) with IN100 scenario results (Figure 4d) shows that when 100% of the SGW is reinjected into the system, boiling does not occur and the vapour-dominated shallow steam zone does not develop. Reinjection of only 50% of the SGW significantly decreases the formation of the two-phase zones (Figure 4c). However this decrease is not as great as for the IN100 scenario. For a still lower reinjection rate (IN25 scenario), the vapour saturation is slightly less than that for the BASE scenario (Figure 4b).

The effect of the different rates of reinjection on the natural recharge from the base and the sides of the system is shown in Figure 5a and 5b, respectively. The recharge history is plotted for all scenarios. As expected, a lower reinjection rate results in more recharge from the side boundaries and from the bottom of the system. Since there is a small rate of reinjection at the later times for the BASE scenario (~23%), the amount of recharge from the side boundaries is similar for the IN25 and BASE scenarios.



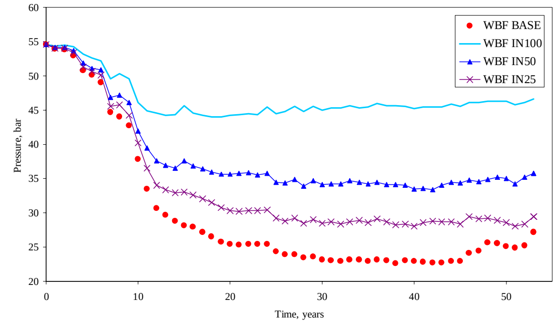

(a)



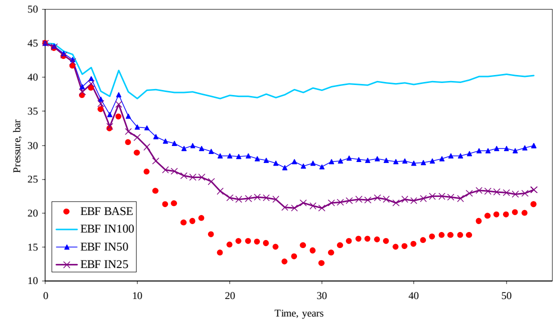

(b)

*Figure 5. (a) Deep recharge and (b) side recharge for the BASE, IN25, IN50 and IN100 scenarios.*

The pressure histories for the BASE scenario are compared with the pressure histories for the three infield reinjection scenarios (IN100, IN50, IN25) for the Western Borefield and Eastern Borefield in Figure 6a and Figure 6b respectively. For the pressure histories, the grid-blocks in the middle of each production area (e.g. BC 35 for the Western Borefield) are used.




(a) Western Borefield



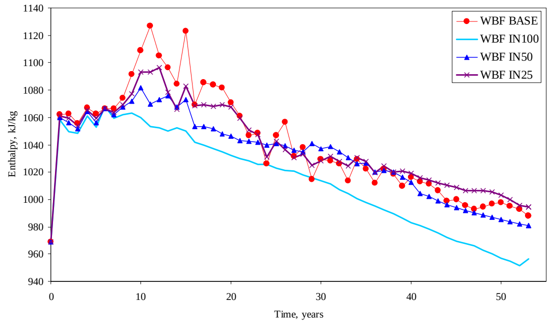

(b) Eastern Borefield

*Figure 6. Pressure histories for the BASE, IN25, IN50 and IN100 scenarios for: (a) Western Borefield, (b) Eastern Borefield.*

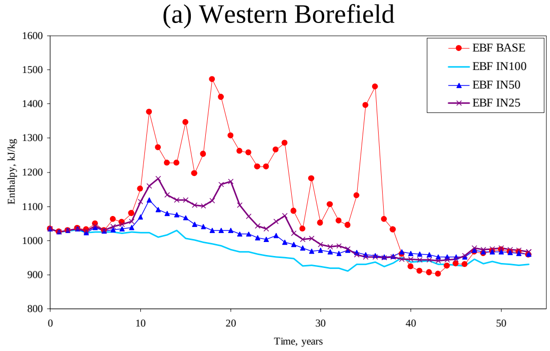
The consequences of strong hydraulic communication between the reinjection and production zones can be seen in Figure 6. Because of this communication, infield reinjection supports the reservoir pressure. The highest pressure increase, (relative to the BASE case) from infield injection occurs for the IN100 scenario, which has the highest rate of reinjection. A decrease in the reinjection rate decreases the pressure support.

The impact of infield reinjection on production enthalpies is shown in Figure 7. According to Figure 7a (Western Borefield) and Figure 7b (Eastern Borefield), for the BASE scenario, after about 5 years of production, the production enthalpy for both production areas increases due to the formation of two-phase zones with high vapour saturations. However for IN100, the production enthalpy decreases rapidly after about 10 years. The main reason for this enthalpy drop is that the high rate of infield reinjection suppresses boiling (see Figure 4b). Additionally infield reinjection increases the reservoir pressure and prevents deep recharge of hot fluid into the reservoir.

When the amount of reinjection is decreased, the detrimental effect on the enthalpy is also decreased. However for the Eastern Borefield (Figure 7b), even with the 50% reinjection of SGW, the detrimental effect of reinjection is still significant.




(a) Western Borefield




(b) Eastern Borefield

*Figure 7. Production enthalpy histories for the BASE, IN25, IN50 and IN100 scenarios for: (a) Western Borefield, (b) Eastern Borefield.*

Because the Eastern Borefield area is much closer to the infield reinjection zone, the difference in enthalpy between the BASE and IN100 scenarios is much higher for the Eastern Borefield wells than for the Western Borefield wells.

For the Western Borefield area, the fluctuation in the production enthalpy between that of water and dry steam indicates boiling in the reservoir takes place for the IN25 scenario as well as for the BASE scenario (Figure 7a). In the long term (after 20 years) reinjection of 25% or 50% of SGW does not have any detrimental effect on the production enthalpies in the Western Borefield.

Figure 7a shows that after about 40 years, production enthalpies for the Western Borefield are similar for the BASE scenario and the IN25 scenario. This is to be expected as for the BASE scenario, after about 40 years, an average of 23% of the total produced mass is reinjected.

**Effect of infield reinjection on surface features**

Two-phase geothermal systems may exhibit a wide range of surface geothermal phenomena including springs, geysers, fumaroles, steaming ground etc. At Wairakei production resulted in the decline of hot springs and geysers and an increase in steaming ground (Glover et al. (2001)). Many hot springs in the Geyser Valley declined and ceased flowing during well testing (1950–1958) or during the early stages of development (1958–1964) (White and Hunt (2005)). Some shallow aquifers near the Eastern Borefield, the Alum Lakes and North Tauhara have gradually declined in water level and chloride content with time (Bromley (2008)). After production commenced, steam flow to the surface increased and this enhanced steam-fed geothermal features. For example numerous new fumaroles and steaming craters formed in Karapiti (Glover *et al.* (2001), Bromley (2008)).

The locations of surface features in the model are shown in Figure 8. In the model the springs are represented by wells on deliverability, located in “spring blocks” mostly in the AR layer (just below the cap, -225masl). The spring blocks in the model are divided into three groups:

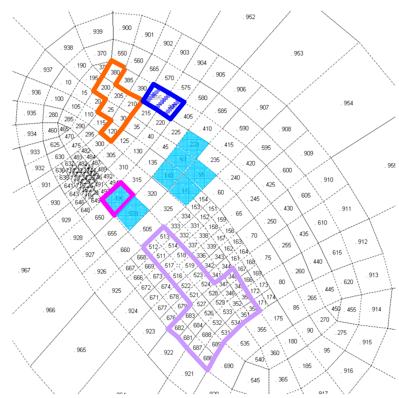


*Figure 8. Location of surface features. The orange, pink, and purple borders show the North, Middle and South zones respectively. The dark blue border shows Geyser Valley. Infield reinjection take place in the blue areas.*

1- North: This includes the Te Mihi, Alum Lakes and Waiora features located in this region (Bromley (2008)). The blocks are shown by an orange bordered area in Figure 8.

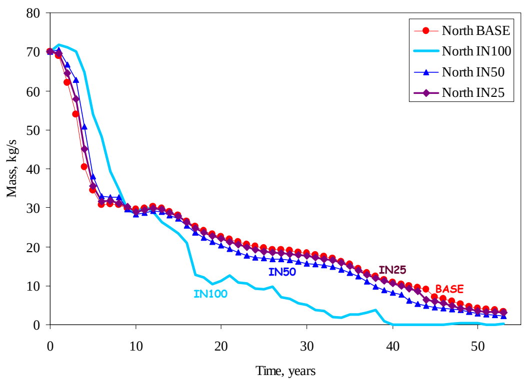
2- Middle: This represents the Karapiti thermal area (Bromley (2008)). It is shown as a pink bordered area in Figure 8.

3- South: The features in the Tauhara region are included in this group. They include: Spa Park, Otumuheke Spring, Otumuheke Stream, Broadlands Road Reserve, Crown Rd (motor-cross), Crown Park, Waipahihi-Lake Front, Waipahihi Source spring, South SH5 and SH5-Mountain Rd (Bromley (2008)). They are within the area inside the purple borders in Figure 8.

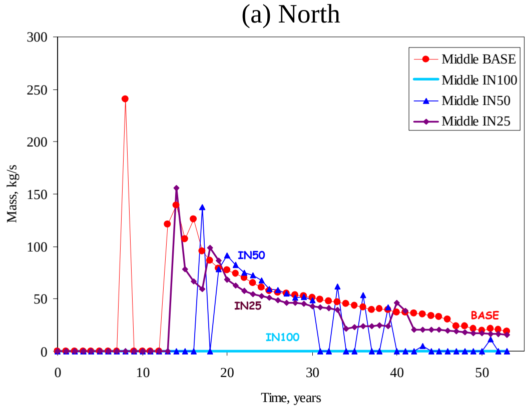
Geyser Valley is one of the major thermal areas in the field that is not represented by spring blocks in the model. Instead it is represented by a hot flow directly to the surface. The dark blue bordered and hatched area in Figure 8 shows the location of these features.

The locations of the infield reinjection wells are shown as blue shaded areas in Figure 8.

The effects of infield reinjection on the mass flow from the North zone (the grid-blocks bounded with orange line in Figure 8) and Middle zone (the grid-blocks bounded with pink line in Figure 8) for all reinjection scenarios are shown in Figure 9a and b, respectively.




(a) North




(b) Middle

*Figure 9. Mass flows at the North and Middle spring blocks for the BASE, IN25, IN50 and IN100 scenarios.*

As shown in Figure 9a, pressure support from a high amount of infield reinjection (IN100) slows the rate of decline of the mass flow at the north spring wells for the first 9 years of the production. However after 9 years, a larger mass flow decline occurs for the IN100 scenario than for the BASE and other scenarios. The high hydraulic communication between the reinjection zone and the North spring blocks causes a breakthrough of injected fluid that cools the zone lying over the reservoir and prevents the formation of steam zones in this area.

The results for the IN50 and IN25 scenarios are very similar to those for the BASE scenario.

As is shown in Figure 8, the middle spring blocks, representing the Karapiti area, are within the infield reinjection zone. The spring blocks are located between the levels of +250masl and +100masl while reinjection is carried out into two different zones between +150masl and +50masl and between -50masl and -150masl. Figure 9b shows that a very high amount of spring discharge starts after about 10 years of production for the BASE scenario. The reason for this discharge is the expansion of the steam zone as a result of a high pressure drawdown and upflow of steam to the surface. A further decrease in the pressure causes a decline in the mass flow. However for the IN100 scenario, no discharge occurs from this block from the very beginning of production until the end.

For the IN50 scenario, since the pressure support is not as high as for the IN100 scenarios, boiling occurs in the reservoir and this causes an intermittent mass discharge (Figure 9b). For the IN25 scenario the mass flow is slightly lower than for the BASE scenario.

The effects of infield reinjection on the mass discharge from the Geyser Valley thermal area are shown in Figure 10. The results show that for all scenarios the mass flow from the Geyser Valley area decreases for about the first 20 years of production. After about 20 years the mass flow continues to decline for the BASE, IN25 and IN50 scenarios but for the IN100 scenario the mass flow levels off and even increases by a small amount. For the IN100 scenario, reinjection stops the pressure decline and supports up-flow from the reservoir. This causes a small increase in the mass flow rate at the later stages of production.

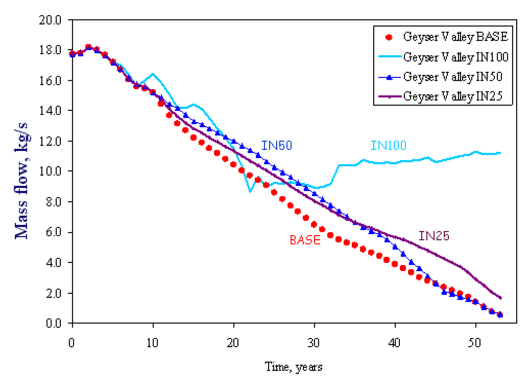



*Figure 10. Mass flows for the BASE, IN25, IN50 and IN100 scenarios for Geyser Valley.*

Again the results for the IN50 and IN25 scenarios are quite similar to those for the BASE scenario.

## SUMMARY

<u>Outfield reinjection:</u> Because the permeable connection between the reinjection zones and production areas is weak, outfield reinjection does not have any effect on the reservoir pressure or production enthalpies. Therefore outfield reinjection is a safe method for disposing of water without risking the detrimental effects of cold reinjection.

<u>Infield reinjection:</u> Without infield reinjection there is a large pressure drop in the reservoir which causes boiling in the reservoir and hence results in the formation of high saturation boiling zones and an increase in production enthalpy. Infield reinjection reduces the pressure decline and thus reduces (or prevents) the increase in the steam fraction, the formation of steam zones and the increase in production enthalpy.

Since pressure is maintained by reinjection, natural hot water recharge to the system is suppressed. Infield reinjection of 50% of the separated water causes considerably less thermal degradation than 100% reinjection, but still causes a decrease in energy production due to the decline in production enthalpy. A still lower rate of reinjection (25% of the separated water) does not cause a significant pressure drawdown or temperature decrease. Thus this scenario appears to be a good infield reinjection strategy.

<u>Surface features:</u> Infield reinjection causes a significant decline or disappearance of steam-fed surface features, if the reinjection zone is close to the surface features. On the other hand infield reinjection supports the flow of chloride water to surface features, but at a lower temperature than in the natural state.

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