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Computer Modelling of Reinjection in Geothermal Fields

Eylem Kaya

A Thesis Submitted in Partial Fulfilment of the Requirements for the Degree of Doctor of Philosophy in Engineering Science

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Abstract

This thesis describes a computer modelling study of reinjection into geothermal systems. The aim of this work was to decide on optimum reinjection strategies for various types of geothermal systems.

First an idealized 3D closed model used by Sigurdsson et al. (1995) is extended to examine the effect of the natural recharge from groundwater, from the basement and laterally from the boundaries of the system. The results show that injection increases steam flow if recharge is small because the reservoir is acting as a closed system, or if the caprock is permeable and allows groundwater recharge. Otherwise injection may cause a decrease in steam production by suppressing hot recharge from depth or replacing lateral recharge by colder injected water.

For hot-water reservoirs the effect of different well configurations on the production performance is examined with a model of the East Mesa field and the results show that deep far-infield reinjection provides an optimum strategy that supports reservoir pressures without causing an early thermal breakthrough.

The impacts of different rates of infield and outfield reinjection on two-phase liquid-dominated reservoirs are investigated by using a model of Wairakei-Tauhara. The results show that outfield reinjection is a safe method for disposing of water. A high rate of infield reinjection prevents boiling in the reservoir and causes a drop in the production enthalpies. A significant decline occurs in the surface features which are close to the injection zones. Reinjection infield of 25% of the separated geothermal water appears to be a good strategy since it does not cause a significant pressure or temperature decrease.

For two-phase vapour-dominated reservoirs reinjection impacts on steam production are investigated by using a model of Darajat. Investigation of various production/reinjection schemes show that; reinjecting 50% of the condensate above the production zones increases steam production significantly. However for higher reinjection rates, the steam production rate may decline owing to the breakthrough of cold reinjected water. If the production zones are deeper, reinjection is much more beneficial. Introducing a larger number of production and reinjection wells scattered throughout the field increases the reservoir life.
This dissertation is dedicated to my mother,

Gülsüm Kaya
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Chapter 1. Introduction and Review of Reinjection Experiences

1.1 Introduction and outline of the thesis

Reinjection of water into a geothermal system during utilization is intended to serve two purposes: (a) improved resource recovery and (b) waste water disposal. To be able to accomplish these two purposes and provide good field management, careful design of the reinjection system is required. This design should balance the requirements to sustain the reservoir pressure and to prevent early breakthrough of cold reinjected water. Also the effects of reinjection on the natural hot recharge, and therefore on energy recovery from the system may be important.

The purpose of the present work is to use computer modelling of reinjection into geothermal fields to decide upon optimum reinjection strategies. The literature survey presented in this chapter indicates that the design of reinjection is most often empirical and site-specific, because the effect of injection on production depends on the structure of the individual system. However there are some generic similarities depending on whether the system is vapour-dominated, liquid-dominated or hot-water. Therefore in this study we investigate the effect of reinjection in these three different types of geothermal reservoirs.

To decide the best reinjection strategy for each type of system it is important to recognize the dominant depletion mechanisms. For the three types of systems these mechanisms can be summarized as follows:

a) Two-phase vapour-dominated systems run out of water while heat still remains in the rock matrix. Therefore it is useful to reinject water infield, above the
depleted reservoir (Cappetti and Stefani (1994), Pruess (1995), Stark et al. (2005), Cappetti and Ceppatelli (2005))

b) In two-phase, liquid-dominated systems the pressure drop at the production wells is buffered by the boiling process. Therefore these systems do not suffer from an excessive pressure decline. Also because these systems typically have good permeability they experience strong lateral recharge and do not run out of water. Rather they slowly cool down as boiling water and steam are extracted and are replaced by cooler recharge. Often reinjection in this type of system has resulted in adverse thermal breakthrough and a consequent move of reinjection out of field, e.g. Cerro Prieto (Lippmann et al. (2004)), Tiwi (Sugiaman et al. (2004)).

c) Because boiling does not occur in hot-water systems, for this type of reservoir the failure mechanism is pressure decline, to the point where wells can no longer produce. Reinjection assists by providing an extra mass flow and by boosting pressures. The ideal reinjection strategy requires the injection wells to be close enough to the production wells to provide pressure support but far enough away to prevent premature flooding by cold water. In some fields, particularly those with a few large faults, thermal breakthrough has occurred rapidly, e.g. Brady (Krieger and Sponsler (2002)), Beowawe (Butler et al. (2001)).

The thesis has the following structure:

In Chapter 1 a literature review of past work on modelling of reinjection in geothermal reservoirs is presented. The past experience of reinjection practices in electricity producing geothermal fields worldwide is analysed and summarised.

Chapter 2 discusses an idealised model that is used to investigate the effects of reinjection on production. The simple model used is a 3D closed box used by Sigurdsson et al. (1995) and Sigurdsson and Stefansson (1998). The Sigurdsson model was chosen as a reference case but his model is extended to investigate the effect of the natural recharge from shallow groundwater, from the basement of the system and laterally from the boundaries of the system.
In Chapter 3 the effect of different well configurations on the production performance of hot-water geothermal systems is discussed. The discussion is based on numerical experiments with a model of the East Mesa field.

To investigate the effect of reinjection on liquid-dominated two-phase systems an existing computer model of the Wairakei-Tauhara reservoir is used to carry out numerical experiments (discussed in Chapter 4). By using scenarios with different rates of reinjection infield and outfield, the effects of reinjection on optimum heat recovery and pressure maintenance are investigated. Additionally, the effect of different reinjection strategies on surface manifestations is analysed.

In Chapter 5, the effect of reinjection on the performance of vapour-dominated geothermal systems is discussed. The model used for the numerical experiments described in this chapter is loosely based on the Darajat system. Different model parameters and various aspects of model design are tried to test the effect of various reinjection strategies on production.

Chapter 6 gives a summary of the work and discusses possible future work.

1.2 Literature review of modelling reinjection in geothermal fields

1.2.1 Simple models, analytical methods

Bodvarsson (1972) considered a homogeneous and isotropic porous and permeable formation saturated with an incompressible fluid to study propagation of thermal fronts for single-phase flow in homogeneous porous media. He derived analytical models for flow through a horizontal, single-layer and infinite fracture. By neglecting thermal conduction as unimportant relative to advection, he developed analytic solutions of the governing equations and revealed two important points: the temperature front lags the fluid front by a constant related to the ratio of rock/water volumetric heat capacities, and there is an abrupt change from the initial temperature to the injection temperature. The study showed that thermal effects of the reinjected water may extend several kilometres from the points of injection and
concluded that injection wells may have to be sited at a considerable distance from the active parts of the reservoir.

Kasameyer and Schroeder (1975) used an analytical model, based on a series of linked boxes between the injection and production wells, to examine the thermal depletion of a liquid-dominated geothermal system. Heat transfer from the rock to the fluid by conduction both in fractures and in pores is considered and heat transfer by the flow of fluid through the pores is accounted for in their model. The reservoir in their model consists of three components: the rock matrix, fluid in interstitial pore space and fluid in the fractures. Three coupled differential equations represent their idealised model. They modelled the fractures by a series of channels between parallel plates. Kasameyer and Schroeder (1976) applied this model to the Salton Sea geothermal field to predict the useful lifetime of the reservoir. They also used the model to simulate the behaviour of Raft River which is a fracture-dominated system.

Tsang and Tsang (1978) developed an analytical solution for modelling the injection of cold water into a single-layer hot reservoir. They treated the 1D radial flow as a moving boundary problem. Their results show that the transient pressure curve initially follows the Theis solution with parameters corresponding to the reservoir hot water. At later times the transient pressure curve becomes parallel to the Theis solution with cold water parameters. They used the results of this model for the analysis of cold water injection tests.

Rahman et al. (1984) studied the progression of the temperature front associated with a geothermal well doublet in an aquifer with ambient temperatures of 70°C and 150°C. They developed a mathematical model for an aquifer of uniform thickness and of infinite horizontal extent. They assumed a homogeneous and isotropic aquifer with an initially uniform temperature distribution. Their study shows that: (i) if the aquifer is thick and the well spacing is large, the progression rates are the same for different temperatures, (ii) for a relatively small aquifer thickness or a short distance between the wells there may be premature cold water breakthrough by a "finger" of fluid.
Pruess et al. (1987) developed an analytic solution of the mass and energy balance equations to simulate reinjection of cold water into a porous medium containing superheated vapour. They developed an approximate solution for temperature (or pressure) and vaporization rate at a moving boiling front. They showed that the rate of boiling at the boiling front is a function of injection rate, degree of superheat initially present in the reservoir and various reservoir properties (e.g., permeability, porosity, and thermal properties).

Woods and Fitzgerald (1993) extended that work (Pruess et al. 1987) and developed an analytical model which describes the generation of vapour following the injection of cold water into a hot, vapour-saturated, porous rock of large extent. They considered one, two and three dimensional models and showed that the geometry of injection (either from a point, line or planar source) has an important effect upon the mass fraction of water that vaporizes.

Garg and Pritchett (1989) derived analytical solutions for the radial flow of mass and heat associated with cold water injection into a single-layer porous medium reservoir. They considered single-phase and two-phase initial conditions. They verified the applicability of their solutions by using a numerical simulator. According to their results, in a single-phase liquid-dominated reservoir, the fall-off pressure after cold water injection (except for very early shut-in times) primarily depends on the kinematic viscosity of the in situ fluid.

Kocabas and Horne (1990) developed a method for forecasting the thermal breakthrough time during injection. Using the Lauwerier model which represents the heat transport in a system consisting of a fracture located in a porous matrix they determined the thermal breakthrough time from the water transit time and thermal interaction between the fracture and the adjacent matrix.

Satman (1988a) and Satman (1988b) developed analytical solutions for describing the temperature distribution and for analyzing the pressure transients in a naturally fractured geothermal reservoir. The model consists of a production (or injection) well fully penetrating a reservoir containing equally spaced horizontal fractures. He noted that these solutions can be used to determine the temperature profile, to estimate the reservoir volume affected by the injection of cold water and to
estimate the amount of heat that can be extracted from the reservoir as the result of reinjection.

Stopa and Wojnarowski (2006) developed a 1D, horizontal, analytical model for determining the velocity of a cold front in a geothermal reservoir. They showed that the variable heat capacity of rock leads to a temperature-dependent speed of propagation of the thermal front.

Malate and O'Sullivan (1992) studied the non-isothermal problem of injection of silica-rich fluid into reservoir. They investigated transport and deposition of silica in a porous medium and in a single fracture medium by deriving analytical solutions for 1D and radial flow. They simulated the effect of temperature of the injected fluid on silica precipitation and found that for a constant inlet concentration of amorphous silica, the rate of silica precipitation increases as the injection temperature is increased. They carried out modelling studies for the case of constant temperature injection into either hot or cold reservoir. Their modelling results show a larger amount of silica deposition for injection of 100°C water into a cold reservoir than into a hot reservoir.

An analytical and numerical study was carried out by Bodvarsson and Tsang (1982) to establish criteria for determining the location and flow rates for injection wells, using the same type of numerical model as that used by Bodvarsson and Tsang (1980). In their analytical work, the rock matrix associated with the fracture is assumed to be impermeable and only the effects of thermal conduction are present. In the numerical study a permeable rock matrix was considered. Using these models, they investigated two simple examples, a hypothetical doublet and geological model of Cerro Prieto field, to calculate the breakthrough times of the reinjected fluid.

1.2.2 Semi–analytical methods

Gringarten and Sauty (1975) used a two-dimensional semi-analytical model to investigate the effect of injection wells on neighbouring production wells.
O'Sullivan and Pruess (1980) developed a semi-analytical method for calculating the radial flow induced by the injection of cold water into a single-layer geothermal reservoir. Their method enables the analysis of injection tests for two-phase or single-phase reservoirs.

Bovarsson and Lai (1982) developed a semi-analytical model for studying the injection of cold water into naturally fractured, liquid-dominated reservoirs. Their model consisted of rectangular matrix blocks bounded by three sets of orthogonal fractures. The results obtained using the model showed that initially the cold water will move very rapidly through the fracture system away from the well. Later on, conductive heat transfer from the rock matrix blocks will retard the advancement of the cold water front, and eventually uniform energy sweep conditions will prevail.

Pruess and Bodvarsson (1984) studied thermal breakthrough in vertical fractures by using a mixed numerical/semi-analytical 3D approach to evaluate the thermal response of fast-paths (preferential flow paths) to injection. They modelled fluid and heat flow in injection-production systems, with heat transfer to and from the adjacent rock matrix. For their semi-analytical model (2D) they considered a vertical fracture embedded in impermeable rock of uniform thermal properties and infinite lateral extent. They incorporated this model with a 2D numerical model by using the MULKOM simulator and considered the physical effects that were neglected in their analytical model (buoyancy, hydrodynamic sweep efficiency etc.). To represent typical fast-path conditions in the numerical model, they carried out injection at two different heights at the left end of the system and production from the right end at the same heights as the injection wells. Their model showed that rapid tracer returns are not necessarily indicative of rapid thermal interference but they indicate a preferential flow path. According to their experiments, if thermal interference along a preferential flow path causes unacceptable declines in production temperature, shutting in the injection well should provide substantial thermal recovery within a few months.
1.2.3 Simple models, numerical methods

Pritchett *et al.* (1977) investigated the effects of injection on the temperature of the produced fluid by using a numerical geopressed reservoir simulator. Their simulator considers the driving mechanisms which tend to expel fluid from the reservoir (e.g. water compressibility, pore collapse, evolution of methane gas, and clay dehydration) and which tend to impede fluid flow (decrease in permeability which accompanies pore collapse, relative permeability effect due to evolution of gas). They set-up a 2D model in which the well layout consists of an array of 56 production wells, 49 "high rate" injection wells and 14 "low-rate" injection wells, for a total of 119 wells.

Lippmann *et al.* (1977) used a numerical 2D (r-z) model to study the temperature, pressure and consolidation behaviour of a liquid-dominated geothermal reservoir in response to reinjection. Both production and injection are applied at the centre line of the model. In some cases one well is used first as an injector and later as a producer, while for other cases production and injection is carried out at different levels. Different injection-production schemes were analysed to explore how to optimize thermal recovery. Their study showed the advantages of reinjection into the lower zone of reservoir and production from the upper zone. They found out that the pressure response is significantly affected by the temperature dependence of viscosity. They coupled a one dimensional consolidation model with the heat and fluid flow model to explore consolidation associated with fluid withdrawal.

Schroeder *et al.* (1982) carried out several simulations of reinjection into vapour-dominated reservoirs using various models. They studied the following problems:

1) Injection of cold water into a thin (single layer) reservoir: They modelled 1D radial flow, in a single layer, near an injection well to study the propagation of hydrodynamic and temperature fronts. They used the results of this simulation to examine the applicability of their technique for the determination of formation parameters from a single-phase pressure transient analysis.

2) A five-spot production/injection configuration in a thin (single-layer) reservoir: They investigated the effect of reinjection for mixed production-injection schemes
using an areal two dimensional mesh. They found that production pressures and
the power output change little due to injection, whereas the longevity of the field
can be substantially increased.

3) Injection of cold water into a thick (multi-layer) reservoir: They studied gravity
effects for injection into a thick two-phase reservoir within a vertical two
dimensional radial mesh. Then they compared the results for shallow and deep
injection and showed that gravity effects can be very strong in thick reservoirs.

4) Injection of cold water into a 1-D vertical column, representing a cross-section
of the Larderello geothermal reservoir. By using this model they studied the
effects of injection at different depths in the more depleted zones of Larderello
reservoir. They found that sharp fronts and phase transition conditions cause
oscillation problems as a consequence of finite space discretization. They
concluded that injection into superheated steam zones may increase production
rates as well as energy recovery.

Bodvarsson et al. (1985) carried out numerical experiments to investigate the effect
of injection on the behaviour of production wells completed in a single-layer
fractured two-phase geothermal reservoir. The grid-blocks are very small around
the wells and larger further away. The fractures are modelled with the MINC
method (Pruess and Narasimhan (1985)). They carried out simulations for a 5-spot
production/injection pattern varying the well spacing, fracture spacing and
injection fraction. The results of their experiments showed that injection tends to
reduce the vapour saturations in the fracture system by flooding and condensation.
This in turn, increases the mobility of the fluid which results in increased flow rates
and decreased enthalpies at the production wells. According to their results, in the
long term reinjection can increase the usable energy output as it helps to extract
energy from the reservoir rock.

Calore et al. (1986) performed simulation experiments on 1D linear and 1D radial
numerical models (using the MULKOM simulator) of porous and fractured
reservoirs in order to study the migration of reinjected water.
Using a 3-D simulator, Bodvarsson and Tsang (1980) studied the radial movement of the thermal front through fractures relative to its movement in the adjacent porous matrix during injection. The model they considered has equally spaced infinite horizontal fractures. The study shows that with conduction alone (no permeability in the matrix) heat transfer from the rock matrix to the fracture will heat the water and retard the movement of the thermal front in the fracture. They observed that the larger thermal conductivity, the more the retardation in the advancement of the front along the fractures.

Nakao and Ishido (1998) carried out numerical simulations of radial flow in a horizontal single-layer fractured medium model to examine the pressure behaviour of reinjection wells where sometimes the pressure initially increases then declines as reinjection continues. They explained the gradual pressure decline during cold water reinjection as resulting from a porosity increase due to cooling and pressure build up. According to their study, there is a large increase in permeability around the well due to the opening and/or induced connection of existing fractures.

Shook (2001b) showed that a finite injection (slug) tracer test can be used to predict the velocity (and therefore breakthrough time) of temperature fronts in single-phase, heterogeneous, porous (i.e. non-fractured) permeable media. They used 2D areal and vertical numerical models. They introduced variable transformations that enable tracer return data (tracer histories) to be used to predict temperature histories.

### 1.2.4 Modelling studies on real fields

Tsang et al. (1984) and Tsang et al. (1981) used idealized models to determine the best reinjection strategies for the Cerro Prieto geothermal field. The model used in these studies is a two-dimensional, vertical slice consisting of two reservoirs with an intervening layer between them. The model includes single and two-phase flow. They tried different schemes with reinjection at various depths and positions within the field. They experimented with different boundary conditions.
Chapter 1. Introduction and Review of Reinjection Experience

According to their results the effect of reinjection on pressure drawdown is significantly less for the open boundary case. They found that thermal breakthrough is strongly dependent on the location of the injection wells. Their results indicate that reservoir pressures will be adequately maintained even when an intervening layer of low permeability is present. Existence of a low permeability intervening layer does not prevent penetration by the reinjected fluid and cooling in the lower reservoir. However if injection is carried out into the lower reservoir, thermal effects are localised in the lower reservoir and the upper reservoir is not affected.

Pruess and Enedy (1993) developed conceptual and numerical models to explain the strong interference of reinjection with a neighbouring production well. Their reservoir model has a vertical fracture (X-Z) embedded in a large radially symmetric layered (R-Z) system. Although the fracture itself requires only a 2-D grid, consideration of fluid and heat flow between the fracture and the surrounding reservoir rock makes the system three-dimensional. In this model all injected water enters one single fracture, and all production comes from the same fracture. Since reinjection causes a temperature decline in the injection plume and a drop in vapour pressure, the steam production decreases. The temperature decline depends on the injection rate and on the heat transfer capacity of the reservoir. They indicate that reinjection should not be concentrated into a few wells. Reinjection wells should be generally operated at below their capacity for accepting fluids due to the heat transfer limitations.

Schroeder et al. (1982) used a one-dimensional vertical column model to approximately represent Larderello and to study the effects of injection at different depths in the depleted zones of the reservoir.

Shook and Faulder (1991) set-up a 3D model with a regular grid structure to investigate the effect of various reinjection schemes on the reservoir response at The Geysers. It was based on the geothermal simulator TETRAD. They assigned typical pressures and temperatures from the field as initial conditions. They compared the results of variety of injection schemes in order to identify the most efficient uses of available reinjection fluid. They found that increasing the fraction
of reinjected mass results in local quenching of the reservoir, and above some threshold fraction of reinjection, the fluid should be reinjected as far from production wells as possible. Their study showed that, while increasing the fraction of mass reinjected results in a delay in energy recovery, it also results in an increase of total energy recovered. The delay in steam recovery can probably be reduced through careful management of wells that show excessive water production.

Axelsson et al. (1995) developed a simple fracture zone model and a simple lumped-parameter model to simulate tracer returns and to predict the temperature of produced water for various reinjection scenarios in order to assess the benefits of long-term reinjection. Their modelling studies were based on reinjection experiments in several low-temperature areas in Iceland. The simple fracture-zone model they used is one-dimensional channel in which the production and reinjection wells are located. In this model the reinjection return is controlled by the distance between the injection and production wells, by the fracture-zone volume and by dispersion. Their simple lumped model consists of two interconnected tanks. The first tank simulates the geothermal system next to the injection well. The second tank simulates the part of the geothermal system around the production well. Their results show that increasing the reinjection rate would decrease the temperature of the produced fluid for some production wells in the Gata and Thelamork fields. Their predictions for the Thelamork field showed that the limited reinjection of warm rather than cold water should result in a higher heat recovery.

Mannington et al. (2004a) investigated the effects of infield reinjection by testing various scenarios for the injection of separated geothermal water and condensate for the Wairakei-Tauhara system. They used a 3D model of Wairakei-Tauhara developed by Mannington et al. (2000) and Mannington et al. (2004b). The results of their experiments show that the best option for maintaining the useful life of the resource is to keep the reinjected fluid as far away from production zones as possible. They indicated that outfield reinjection near the field, low levels of infield reinjection, or possibly a combination of these two, should be the preferred
options. They showed that for a two-phase liquid-dominated system like Wairakei-Tauhara high levels of infield reinjection are not desirable.

Sullera and Horne (2001) examined injector-producer connectivity in Dixie Valley, Nevada and Palipinon-I, Philippines reservoirs. They used multiple regression techniques to correlate the isolated short-term variations in chloride with corresponding short-term fluctuations in injection rates.

A 3D numerical modeling study was carried out by Akin et al. (2003) to simulate the effect of reinjection on the Kizildere geothermal field, using the STAR geothermal simulator. They set up three different reservoir models: isothermal, non-isothermal and non-isothermal with CO₂. They used a regular rectangular grid and a dual porosity approach. They tried several reinjection locations: at the center of the field, corners of the field and sides of the field. Several different injection rates were also considered in this study. Their results show that: i) for high injection rates the overall temperature decrease is less if reinjection is carried out from corners, but the pressure drop is the highest, ii) reinjection near the center of the field resulted in better pressure support but caused cooling, and iii) for high reinjection rates, the reservoir cools faster.

Satman et al. (2005) investigated the production/reinjection behaviour of Kizildere geothermal field, which has shallow and deep zones in hydraulic communication. They used a lumped-parameter model that assumes the reservoir is liquid-dominated and contain single-phase compressed water. They tried several variations of the lumped-parameter models to simulate different type of recharge: (A) one-reservoir with a recharge source, (B) one-reservoir – one aquifer, with and without a recharge source (C) one-reservoir - two aquifers, with and without a recharge source, (D) one shallow reservoir - one deep reservoir with a recharge source, and (E) one shallow reservoir - one deep reservoir - one aquifer with a recharge source. They investigated several production and reinjection scenarios such as 1) production and reinjection for both zones, 2) deep production and shallow reinjection, or vice versa. The results of their modeling study indicate that the scenarios with the high rate of production from the deep reservoir give a lower pressure drop and thus increase the life of the reservoir. They suggested that the
shallow reservoir should be targeted for reinjection and the deep reservoir for the production.

In the literature there are several other modelling studies that consider reinjection into various geothermal fields. However these studies do not specifically investigate the effect of reinjection on production or they do not evaluate different reinjection schemes or rates and therefore they are not included here.

### 1.2.5 Injection strategies

Lovekin (1987) studied the application of algorithms developed in operations research to the optimization of reinjection in geothermal fields. He investigated two topics; (i) choosing a configuration of injectors from an existing set of wells, and (ii) allocating a total specified injection rate among chosen injectors. He idealized the reservoir as a network of channels or arcs directly connecting each pair of wells in that field. Each arc in the network is considered to have some potential for thermal breakthrough. He optimized reinjection by choosing the locations and injection rates for the injection wells so as to minimize breakthrough subject to constraints on the number of injectors and the total amount of fluid to be produced and reinjected.

Sigurdsson et al. (1995) and Sigurdsson and Stefansson (1998) carried out a modelling study on an idealised reservoir for the purpose of analysing reinjection strategies. They considered various reinjection strategies for models of water dominated, two-phase and vapour-dominated reservoirs. Different permeabilities, porosities and reinjection rates were tried to investigate the effect of reinjection on the power output.

Some of the studies presented above (e.g. Lippmann et al. (1977) and all of the modelling studies on real fields in Section 1.2.4) also evaluate the effect of various reinjection scenarios.
1.2.6 Model design aspects

Reinjection into geothermal systems is a complex phenomenon, especially for the case of cold water injection into a reservoir containing some steam. The reason for this is that the process involves complex fluid flow and heat transfer processes including boiling and condensation with strong latent heat effect. Also there is vapour-liquid counter-flow and mixing of waters with different temperatures (Pruess (1991a)). In the literature, experiences in modelling reinjection into geothermal reservoirs show that different representations of the reservoir lead to very different model predictions (Pruess (1991a), Schroeder et al. (1982). Therefore to obtain realistic predictions for practical injection problems that involve multidimensional flow effects on a broad range of space and time scales, different modelling approaches need to be investigated. The studies on the subject involve three main topics: grid size, grid orientation and physical effects. These are discussed below.

Grid size

Space discretization effects on reservoir modelling results are well known from immiscible displacement processes Aziz and Settari, (1979). Effect of grid size on results from geothermal reservoir models were investigated by Pruess (1991a), Schroeder et al. (1982), Pruess and Garcia (2000), Lai and Bodvarsson (1991), Oldenburg and Pruess (2000) Fitzgerald et al. (1994). They all showed that numerical predictions are highly sensitive to the refinement of the grid. A small grid size gives more accurate results, mainly because it diminishes numerical dispersion.

According to Pruess et al. (1979) in problems involving sharp fronts and phase transitions, numerical models exhibit oscillating trends that are related to the level of space discretization. Schroeder et al. (1982) also showed that the amplitude and frequency of the oscillations depends on the space discretization.
Grid orientation

The effect of grid orientation on reservoir modelling results was first investigated in the simulation of steam flooding of petroleum reservoirs by Todd et al. (1972), Coats et al. (1974) and Brand et al. (1991). Todd et al. (1972) compared diagonal and parallel grids for a five-spot simulation, and demonstrated that the predicted recovery depends on the grid orientation. According to Todd et al. (1972), Coats et al. (1974) and Brand et al. (1991) the grid orientation effect becomes more significant as the mobility ratio increases.

Yanosik and McCracken (1979), Coats and Ramesh (1982), Pruess and Bodvarsson (1983) showed that grid orientation effects can be substantially reduced by means of a "nine-point" approximation, which allows for the possibility of flow along diagonal directions.

According to Pruess (1991a) discretization effects that are associated with the orientation of the grid arise in two-phase flow, because they affect the coupling between fluid flow and heat transfer and alter the phase composition of the flowing two-phase mixture. Moreover these grid orientation errors are not overcome by finer discretization.

Pruess (1991a), Pruess (1991b) and Pruess (1995) simulated reinjection into vapour-dominated reservoir by using 2D areal and 2D vertical models and compared the shape of the injection plume for parallel and diagonal grid structures. These studies showed that grid orientation effects are mostly insignificant for the areal models, however they can be very strong for cold water reinjection into low-pressure vapour zones. These studies also indicate that using a 9-point approximation reduces the difference between the results of simulations using parallel and diagonal grids.

Physical effects;

i- Phase dispersion

Pruess (1994a) and Pruess (1995) investigated the effect of phase dispersion on the behaviour of an injection plume by applying a Fickian type dispersion term. These
studies showed that phase dispersion enhances lateral and diminishes the downward movement of the injection plume and neglecting this process may lead to an underestimate of the potential water breakthrough.

Oldenburg and Pruess (2000) implemented the Leonard total variation diminishing (LTVD) schemes into the implicit geothermal reservoir simulator TOUGH2 to obtain an accurate numerical solution for strong advective flows of multiphase non-isothermal flows. They indicate that reinjection simulations with standard finite-difference techniques may erroneously predict early tracer breakthrough because of numerical dispersion effects, leading to an overly conservative reinjection design. They verified the LTVD scheme by comparison with an analytical solution for 2D single phase flow in a fractured media, and claim that the LTVD scheme is a practical method for reducing numerical dispersion in complex flows relevant to geothermal reservoir engineering.

Croucher et al. (2004) showed that the numerical techniques used in most reservoir simulators, based on ‘upstream weighted’ finite differences, can lead to problems with numerical dispersion, since numerical dispersion has the effect of smoothing out sharp fronts in scalar quantities (e.g. temperature, liquid saturation, tracer concentration) transported by the flow. They developed a simulator which uses the Eulerian–Lagrangian method (ELM) in a finite-element context in conjunction with flow fields generated by TOUGH2. This ELM tracer simulator is limited to single-phase problems in two dimensions. They tried this simulator with two analytical problems: i) a 2D line source problem ii) a 2D doublet problem (one production and one reinjection well). Their results show that the ELM simulator almost eliminates the problem of numerical dispersion and produces accurate solutions.

**ii- Formation heterogeneity**

Pruess (1996) analysed the behaviour of an injection plume in heterogeneous media. He generated stochastic permeability distributions, based on the essential characteristics of fractures in hard rock of very low permeability. He suggested that this approach is more realistic than using fractured media with a regular structure, although it still represents a considerable simplification relative to the irregular void space geometry of actual fractures and fracture networks.
iii- Capillary pressure

According to Pruess (1991a) the inclusion of capillary pressure effects substantially eliminates the grid orientation effects.

iv- Viscous fingering

Fitzgerald et al. (1994) showed that at low rates of reinjection, the liquid-vapour interface may become unstable and break up into fingers.

v- Relative permeability

Schroeder et al. (1982) and Bodvarsson et al. (1985) showed that the shape of steam-water relative permeability curves has a significant impact on the modelled performance of geothermal reservoirs. According to Bordvarsson et al. (1985) the Corey curves are not applicable to fractured geothermal reservoirs since the steam flow rate strongly depends on vapour saturation.

vi- Fractured rock model

The double-porosity concept for modeling flow in fractured porous media was developed by Barenblatt et al. (1960) and Warren and Root (1963). In the double porosity concept, the main transport of fluids takes place through the fractures, while the matrix blocks supply the fluids to the fractures. Pruess and Narasimhan (1985) developed a "multiple interacting continua" (MINC) method, which is a generalization of the double porosity model. In this method, each matrix block is divided into a nested subdomain so that the transient flow regime can be represented. Pruess and Narasimhan (1985) and Pruess (1992) implemented this formulation in the Integral Finite Difference (IFD) framework used in TOUGH2.

vii- Mineral precipitation / dissolution

Xu et al. (2008) developed a non-isothermal reactive geochemical transport code (TOUGHREACT) which includes comprehensive chemical interactions between liquid, gaseous and solid phases that are coupled to solute transport and sub-surface multiphase fluid and heat flow. They indicate that changes in porosity and permeability due to mineral dissolution and precipitation or clay swelling can
modify fluid flow path characteristics. They calculated the changes in porosity from changes in mineral volume fractions. Different porosity-permeability relationships are coded in the TOUGHREACT. Therefore their study allows the modelling of the effect of mineral scaling on the injectivity.

**viii- Geomechanical behavior**

Wojnarowski and Rewis (2003) developed a numerical model to determine the impact of reinjection on the geo-mechanical behaviour of a geothermal reservoir. They investigated the evolution of the stress state in a liquid-dominated reservoir, including how principal stress directions change as the injection pressure increase. They used a 2-D reservoir simulator describing fully coupled fluid flow, heat flow and geo-mechanical behaviour. Their simulation results show that when the injection pressure decreases the magnitude of the tensile stresses resulting from cold-water reinjection increases.

### 1.3 Background on reinjection

#### 1.3.1 Classification of geothermal systems

The effect of reinjection on production depends on the structure of the individual system but there are some generic differences depending on the thermodynamic state, geological structure and hydrological characteristics. To provide an optimum reinjection plan, geothermal systems should be evaluated according to their individual characteristics. In this section, to assist with the evaluation of reinjection effects, geothermal reservoirs are classified into five groups, based on the representative characteristics of each reservoir. The criteria used for defining these categories are shown in Table 1-1. However they are not rigid criteria. For example some wells in medium enthalpy systems may have discharge enthalpies greater than 1500kJ/kg. Similarly within a single geothermal system there may be distinct zones of different types. For example at Wairakei there is a shallow
vapour-dominated zone in a predominantly low enthalpy two-phase liquid-dominated system.

Table 1-1 Categories of geothermal systems

<table>
<thead>
<tr>
<th>Category</th>
<th>Temperature (T)</th>
<th>Production Enthalpy (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot-water</td>
<td>T&lt;220°C</td>
<td>h &lt; 943 kJ/kg</td>
</tr>
<tr>
<td>Two-phase, liquid-dominated</td>
<td>low-enthalpy</td>
<td>943 kJ/kg&lt;h&lt;1100 kJ/kg</td>
</tr>
<tr>
<td></td>
<td>medium-enthalpy</td>
<td>1100 kJ/kg &lt;h&lt;1500 kJ/kg</td>
</tr>
<tr>
<td></td>
<td>high-enthalpy</td>
<td>1500 kJ/kg &lt;h&lt;2600 kJ/kg</td>
</tr>
<tr>
<td>Two-phase, vapour-dominated</td>
<td>240°C&lt;T&lt;330°C</td>
<td>2600 kJ/kg &lt;h&lt;2800 kJ/kg</td>
</tr>
</tbody>
</table>

The general characteristics of each type of geothermal systems are summarised below.

**Hotwater systems:**

In this type of systems no boiling occurs before or after production commences. Without any reinjection, when production starts, the pressure will drop until the recharge is induced from the boundaries of the system. This may lead to large pressure declines and loss of productivity.

**Two-phase, liquid-dominated systems:**

In contrast to hot-water systems, boiling occurs in two-phase-liquid-dominated systems. The pressure drop in the reservoir near the production wells is in practice buffered by the boiling process. The pressure declines rapidly until boiling occurs, and then the pressure declines more slowly. It tracks down the boiling curve following the temperature decline resulting from two processes:

- The heat extracted from the rock matrix boils off the water, turning it into steam.
- The cool recharge (mainly water rather than steam) is attracted to the low-pressure zone both from the top and the sides of the reservoir.
In some cases, hot deep recharge offsets the cool recharge or even exceeds the cool recharge, depending on the balance between lateral and vertical permeabilities.

Boiling depends on the permeability structure of the system. In this thesis, we classify the two-phase liquid-dominated systems into three groups based on the boiling conditions.

i) **Two-phase, low-enthalpy systems:** In their natural state these systems contain all or mostly hot water. They are typically generally fractured systems with large permeabilities. A permeability boundary around the hot reservoir does not necessarily exist in this type of systems. The pressure decline in the reservoir due to the production induces natural recharge. Since fractures allow a large amount of fluid flow from the boundaries of the system to the reservoir, the pressure drop is not large, and hence the boiling zone is relatively wet in this type of systems.

ii) **Two-phase, medium-enthalpy systems:** Boiling zones are non-existent or small in the natural state for these systems. They generally have relatively low reservoir permeability, often resulting from a few large fractures within a “tight” rock matrix. When production starts, local boiling near the wells occurs due to the large pressure drop and at least some of the wells discharge at medium enthalpies.

iii) **Two-phase, high-enthalpy systems:** Their permeability structure is very similar to two-phase medium enthalpy systems. They also consist of few major fractures in a low permeability matrix but in this case the volume and/or the permeability of the fractures are somewhat smaller and the boiling zones surrounding the production wells are dryer and thus the production enthalpies are in the higher range. In this case natural recharge is limited by the low permeability and a significant pressure drop may occur.

**Two-phase, vapour-dominated systems:**

Vapour-dominated two-phase systems produce dry steam but they contain large amount of immobile water. These systems have low permeability in the reservoir zone and very low permeability surrounding the reservoir. Hence natural recharge is very limited from the surrounding rocks. As the pressure decreases in this type
of geothermal system during production, more and more of the immobile water boils to form steam which then flows towards the production wells.

1.3.2 Location of injection wells

The location of injection wells relative to production wells is probably the most important issue in the design of a reinjection system. In this chapter *infield reinjection* refers to injection wells located close to the production wells and within the hot part of system – say within the resistivity boundary. *Outfield reinjection* refers to the injection wells further away from the production wells and outside the hot part of system. Unfortunately these definitions are not precise and distances cannot be given definitively.

Some authors (e.g. SKM (2004)) have attempted to define *infield reinjection* and *outfield reinjection* in terms of how well the injection wells and production wells are connected, measured by pressure communication. However this classification requires information that is not usually available, particularly before the injection wells are drilled, and therefore may not be practically useful.

1.4 Review of worldwide reinjection experience

1.4.1 Introduction

A good knowledge of past experience of reinjection practices is of importance for the optimal development and management of a geothermal resource. Therefore we carried out a literature survey of all of the electric power producing geothermal fields in the world to gather information on the worldwide experience of reinjection operations. The results of the survey are discussed in this section. Reports and articles, available in the open literature, on ninety-one electric-power producing geothermal fields were reviewed. Various past and current reinjection strategies
practised in the geothermal fields and the response of different type of geothermal reservoirs to these strategies were investigated.

The review of the reinjection experience for the ninety-one geothermal fields is summarised in the tables given in the appendix for the aforementioned five types of geothermal system. Because of the incompleteness of available information, it was not possible to classify eight of these fields and hence they were listed as unclassified reservoirs.

1.4.2 Information Available

Reports and articles, available in the open literature, on ninety-one geothermal fields were reviewed. In each case we were seeking information about the current power generation, total mass production, average production enthalpy, location and amount of reinjection and any problems associated with production and reinjection. In many cases the information available is incomplete and the summary plots given below are based on fewer than ninety-one fields. According to the data reviewed, the current world total of electrical energy production from geothermal fields is 8443 MWe based on data up to 2008.

The average enthalpy value for each geothermal field and the classification of the fields are shown Figure 1-1.
Figure 1-1  Average enthalpy value for each field and their classification
Figure 1-2(a) and Figure 1-2(b) presents the data in pie-chart form for total energy production (MWe) and bar chart form for mass production per MWe for each type of geothermal system. According to Figure 1-2(a) currently 55% of the geothermal power comes from the combination of two-phase high-enthalpy systems and two-phase vapour-dominated systems. Two-phase medium enthalpy-systems also make a significant contribution compared to the low-enthalpy and hot-water systems. Since they contain a lower energy density than high- and medium-enthalpy systems, hot-water and two-phase low-enthalpy systems require higher rates of mass production per unit MWe of power (Figure 1-2(b)).

![Diagram](image1.png)

**Figure 1-2 (a) Total energy production, MWe and (b) total mass production (t/h) per MWe for each type of geothermal system.**

It should be noted that because of the incompleteness of the information Figure 1-2(a) represents the data from 82 fields out of the ninety-one total (99.7% according to energy production) and Figure 1-2(b) represents data from only 62 fields (84.5% according to energy production).

Some compromises were required in the data shown in the plots, e.g. power production from the Darajat field increased from 145MWe to 259MWe in 2007. Since the only available recent mass production data is from 2005, in Figure 1-2(b), the power production value of year 2005 (145MWe) was used. However in Figure 1-2(a), the most recent power production data (259 MWe) was used for this field.
Figure 1-3(a) and Figure 1-3(b) presents the reinjection data in pie-chart form for total reinjection and bar chart form for reinjected mass per MWe, respectively. As expected the hot-water and two-phase, low-enthalpy systems inject large amounts of water while two-phase vapour-dominated systems have the lowest percentage of total reinjection. For the contribution of vapour-dominated systems in Figure 1-3(a) and Figure 1-3(b) additional surface water reinjection (for Darajat, Larderello and The Geysers) has been included in the charts.

Figure 1-3 (a) Total mass reinjection (t/h) and (b) total mass reinjection (t/h) per MWe for each type of geothermal system.

Figure 1-4 shows total mass production and reinjection (blue), for each type of geothermal system. According to this figure, hotwater systems reinject the highest percentage of produced mass back into the reservoir (80%), while two-phase medium enthalpy reservoirs reinject the lowest percentage (43%) of produced mass.
Figure 1-4 Total mass production and reinjection (blue), (t/h) for each type of geothermal system.

Because of the lack of information available about the amount of reinjection in many of the fields among the ninety-one considered Figure 1-3 and Figure 1-4 represents the data from only 54 fields (82.2% according to energy production).

Figure 1-5 presents mass production per MWe generated for the individual fields, grouped according to their enthalpy classification. The results are affected somewhat by the individual characteristics of the field but the general trends are clear. The fields that produce high enthalpy fluids require less fluid per MWe.
Figure 1-5 Produced mass per MWe energy generated for each field
Figure 1-6 shows the mass of reinjected fluid for each fields per MWe produced, again grouped according to the enthalpy classification. This figure also includes the additional surface water reinjected at Darajat, Larderello and The Geysers. As expected the results show that fields which produce high enthalpy fluids reinject smaller amounts of fluid per MWe.

Figure 1-7 shows the amount of waste water discharged to the surface from twelve fields for which data are available. For some of these fields, the amount of waste water discharged to the surface is not given in the literature. Instead of this, steam and brine production flow rates and percentage of surface discharge of total produced fluid is given. For this type of data, waste water discharge is calculated to obtain the points plotted in Figure 1-7. In these calculations, we simply assumed that the total production rate is equal to the total waste fluid for hot-water reservoirs. However for two-phase reservoirs the waste water rate was taken to be the sum of produced total brine rate and 10% of the produced total steam rate assuming that 90% of the condensate may typically be evaporated through the cooling towers into the atmosphere. This assumption is based on the review of reinjection experiences by Kaya et al. (2009), which shows that steam losses varies between 75-90% (e.g. Ahuachapan about 90%, Mori about 87%, Miravalles about 82% and The Geysers about 75%).
Figure 1-6 Mass reinjected per MWe
1.4.3 Summary of Reinjection Experience

In this part of the study the review of worldwide reinjection experience (Kaya et al. (2009)) is summarized in order to provide general knowledge about worldwide reinjection strategies and the response of different type of geothermal reservoirs to these strategies. For this summary, the location and amount of reinjection, problems and benefits associated with production is taken into consideration.

1. In two-phase, vapour-dominated reservoirs infield reinjection is usually used and very few adverse effects on the thermodynamic state of the reservoir have been reported. In some cases injection has had an important role in maintaining steam production (e.g. Darajat, Kamojang, Larderello, Pohipi). The Geysers field has been affected thermally with temperature and wellhead enthalpy declines being observed. But overall infield reinjection has assisted steam production. Recently additional make-up water has been added to the reinjection (Stark et al. (2005)) and this has significantly slowed the decline in steam production.

Figure 1-7 Waste water discharged to the surface
Chapter 1. Introduction and Review of Reinjection Experience

2. In two-phase, high-enthalpy reservoirs mostly infield reinjection is used. Thermal breakthrough had been observed in Olkaria I, and Bulalo but when the infield reinjection was stopped or was reduced, the affected wells recovered gradually. Chemical breakthrough has been observed in Krafla and Los Azufres, but no changes have been reported in the thermodynamic conditions in these fields.

3. Several of the two-phase, medium-enthalpy reservoirs have experienced thermal breakthrough (e.g. Hatchobaru, Matsukawa, Sumikawa, Cerro Prieto, Palinpinon, Ohaaki) or the precursor chemical breakthrough (e.g. Berlin, Tiwi, Mahanagdong) resulting from infield reinjection. Moving reinjection wells outfield has resulted in the recovery of the production wells.

4. Most two-phase, low-enthalpy reservoirs have experienced thermal breakthrough caused by infield reinjection (e.g. Miravalles, Ahuachapan, Mori, Onikobe). But these fields have recovered when the production-reinjection scheme was changed. Some fields have not been significantly affected by thermal or chemical breakthrough (e.g. Otake and Ngawha). Reinjection returns have been recorded in Dixie Valley field but in this case pressure support from reinjection has helped to maintain production and infield reinjection has been maintained Reed (2007).

5. Most hot-water reservoirs have experienced thermal breakthrough (e.g. Pauzhetsky, Kizildere, East Mesa, Beowawe, Brady, Empire, Steamboat). But infield reinjection has helped with pressure maintenance (e.g. Pauzhetsky, Kizildere). Shifting reinjection deeper to avoid temperature declines may cause an increase in the pressure decline (e.g. Casa Diablo). In some cases moving reinjection wells closer to production wells has had a positive effect by reducing drawdown (e.g. Beowawe).

6. Full or partial surface discharge is still a common practice in many fields worldwide (e.g. Krafla, Nesjavellir, Svartsengi, Momotombo, Husavik, Kawerau, Wairakei, Kizildere, Cerro Prieto, Olkaria I, Los Azufres, Pico Vermelho, Pauzhetsky, Yangbajain, Nagqu, Lihir, Bouillante). However, currently there is general agreement on the important benefits of reinjection in preventing
environmental pollution from geothermal fluids (chemical and thermal), and sometimes in providing pressure support to the reservoir and preventing or reducing subsidence.

7. In most cases the adverse effects of reinjection have been reversed when infield reinjection was abandoned or reduced (e.g. Tiwi, Ahuachapan, Miravalles, Hatchobaru, Uenotai, Bulalo, Tongonan, Palpinon, Onikobe, Mindanao, Olkaria I, Empire). However, long term adverse effects can be seen in a few fields (e.g. Brady, Mori), and to some extent in Mahanagdong (possibly due to reinjected fluid combined with groundwater inflow), where these plants are running at below design capacity after the reinjection was moved outfield. For example, at Brady the temperature and flow rate of the produced fluid decreased after the start of reinjection. After 60% of reinjection was diverted outfield, the fluid production level and temperature did not recover. Similarly at Mori approximately 40% of reinjection has been moved outfield but still there are reinjection returns to the production wells and some of the reinjection returns has been replaced by cold recharge from groundwater.

8. In most cases of long-term infield reinjection thermal breakthrough to production wells has occurred within ten years of service (Ahuachapan, Brady, Bulalo, Coso, Hatchobaru, Kakkonda, Mahanagdong, Matsukawa, Mindanao, Miravalles, Palpinon, Pauzhetsky, Sumikawa, Uenotai, The Geysers, Tiwi, Tongonan, Krafla, Mori, Ohaaki, Onikobe, Empire, East Mesa, Casa Diablo, Olkaria I, Los Humeros, Dixie Valley, Kizildere). The other cases where infield reinjection is not yet causing any thermal breakthrough may be because reinjection has not been running for long enough (Amatitlan, Rotokawa, Mokia, Ngawha, Berlin, Zunil, Salak, Ribeira-Grande, Mutnovsky, Dieng, Wayang-Windu, Los Azufres, Ngawha) or the amount of reinjected fluid is very small (Larderello, Cerro Prieto, Kamojang, Darajat, Krafla, Nesjavellir, Svartsengi, Kawerau).

9. Infield reinjection is a cheap but often temporary method of waste fluid disposal. It is normally undertaken to reduce costs during early stages of field development (Rotokawa, Mokia, Ahuchapan, Salak, Zunil, Ngawha, Amatitlan, Brady) or as a first step in a full scale reinjection strategy in existing
developments (Cerro Prieto, Matsukawa, Tiwi, Wairakei, Olkaria, Ohaaki, Kawerau, Pauzhetsky, The Geysers). In most cases existing production or investigation wells were used for reinjection at first, and these wells were usually located in the middle of the field (Rotokawa, Mokia, Ahuchapan, Salak, Zunil, Lahendong, Ngawha, Amatitlan, Cerro Prieto, Matsukawa, Tiwi, Wairakei, Olkaria, Pauzhetsky, The Geysers, Brady). Reinjection in these wells was abandoned or reduced when the adverse effects of infield reinjection became evident (Ahuchapan, Tiwi, Salak, Matsukawa, The Geysers, Bulalo, Tongonan, Mahanagdong, Brady, Rotokawa).

10. Full reinjection has been achieved in few existing reservoirs (e.g. Ahuachapan, Tiwi). Some other fields (Cerro Prieto, Wairakei, Olkaria) are in the process of decreasing surface discharge by greatly increasing reinjection but may not achieve full reinjection.

11. A reinjection scheme that provides pressure support to the reservoir (infield reinjection) requires a careful monitoring program to prevent reservoir cooling. Cooling can be reversed if mitigation measures are taken promptly.

12. Shallow reinjection can result in increasing flux of fluid to the surface affecting existing natural features (e.g. Rotokawa, Mokai, Tongonan, Kawerau, Dixie Valley) and may help create new features (e.g. Rotokawa, Dixie Valley) fed directly or indirectly from the injected fluid. In some fields shallow reinjection resulted in ground inflation (e.g. Heber, Mokai, Steamboat Hills). These effects are not desirable if they take place within residential areas, agricultural activity areas or within industrial areas. Therefore, shallow reinjection should be planned with caution.

13. An excessive reinjection pressure may make pumping uneconomical (Heber) or operationally unfeasible if it exceed the design pressure of the surface equipments (pipes, valves etc.). An excessive reinjection pressure can also cause hydro-fracturing or induced micro-seismic activity (The Geysers).

14. For some cases where the cap rock is fractured or is not continuous reinjection supports the reservoir pressure and prevents cold groundwater inflow (Namafjall, Mori). Shifting reinjection to deeper parts of the reservoir to prevent
returns and a temperature decline may introduce a pressure decline (Casa Diablo). In one case moving injection wells toward the production wells has had a positive impact by reducing drawdown (Beowawe).

15. The optimum total reinjection strategy for liquid-dominated reservoirs (hot-water, low enthalpy two-phase, medium-enthalpy two-phase) appears to be to have a mix of infield and outfield reinjection. The infield reinjection provides pressure support to the main bore field and reduces drawdown, groundwater inflow and subsidence. The outfield reinjection reduces the effect of thermal breakthrough. The proportion of infield to outfield injection flow rates is case specific and typically the infield reinjection rate needs to vary with time as a part of the steam field management strategy.

16. Experience has shown that reinjection should be planned as early as possible in the field development.
Chapter 2. Icelandic Models

2.1 Introduction

The present chapter describes a computer modelling investigation of the effect of reinjection on steam production in a geothermal reservoir, and in particular its effect on the longevity of the resource. One of the few previous modelling studies on the topic was carried out by Sigurdsson et al. (1995) and Sigurdsson and Stefansson (1998) on an idealised reservoir.

For the present study the Sigurdsson model was chosen as the reference case but it was extended to investigate the effect of the recharge from shallow groundwater, from the basement of the system and from the lateral boundaries of the system. Various cases are considered for different reinjection strategies and for different permeability structures. The geothermal simulator TOUGH2 (Pruess et al. (1999)) was used for all the simulations described in this chapter.

2.2 The Sigurdsson model

The conceptual model for this hypothetical model is based on the Nesjavellir field (see Figure 2-1). Thus the reservoir structure, rock properties and rock type distribution resembles the Nesjavellir field in Iceland (Stefansson (1997), Steingrimsson et al. (2000) and Bodvarsson et al. (1990)).
Chapter 2. Icelandic Models

Figure 2-1 Conceptual model of Nesjavellir field, Steingrimsson et al. (2000)

The grid structure of Sigurdsson’s idealised model resembles the numerical model developed for the Nesjavellir field (see Figure 2-2, Steingrimsson et al. (2000)).

Figure 2-2 Areal view of the grid structure of Nesjavellir field (Steingrimsson et al. (2000))

In Sigurdsson et al. (1995) and Sigurdsson and Stefansson (1998), the effect of reinjection on steam production from the idealised geothermal model was
simulated for three types of systems: hot water, two-phase liquid-dominated and two-phase vapour-dominated. The only difference between these models is the initial conditions. For this study, we only considered their two-phase liquid-dominated model. The two-phase initial conditions used in the Sigurdsson model resemble the natural state conditions at the Nesjavellir geothermal field (Stefansson (1985) Bodvarsson et al. (1990). The initial conditions for this model are shown in Table 2-1.

Table 2-1  Initial conditions for Sigurdsson’s two-phase liquid-dominated model.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Pressure, bar</th>
<th>Temperature, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groundwater</td>
<td>13.9</td>
<td>90.0</td>
</tr>
<tr>
<td>Cap rock</td>
<td>38.8</td>
<td>207.0</td>
</tr>
<tr>
<td>Upper reservoir</td>
<td>65.5</td>
<td>281.0</td>
</tr>
<tr>
<td>Deeper reservoir</td>
<td>93.8</td>
<td>306.2</td>
</tr>
</tbody>
</table>

These initial conditions are very close to the boiling curve and so the reservoir becomes two-phase very soon after production begins.

The Sigurdsson model consists of four layers. The top two layers are 300m thick and correspond to the groundwater system and a cap-rock layer respectively. The other two layers are each 400m thick and represent the reservoir rock.

The areal extent of the layers is 1.6km x 2.0km, with each layer divided into 66 elements, most of size 200m x 200m, but with some of the peripheral blocks twice that size. The detailed grid structure of the model is shown in Figure 2-3, Sigurdsson et al. (1995), Sigurdsson and Stefansson (1998). A subgrid consisting of two radial elements was used around the production wells (O. Sigurdsson, private communication).
Chapter 2. Icelandic Models

Figure 2-3  Areal grid structure of the Sigurdsson model (production wells are red, injection wells are blue)

Table 2-2 shows the reservoir parameters used in the numerical model.

Table 2-2  Model parameters

<table>
<thead>
<tr>
<th>Rock Parameters</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Matrix density, kg/m³</td>
<td>2650</td>
<td></td>
</tr>
<tr>
<td>Specific heat, J/(kg°C)</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity, W/(m°C)</td>
<td>1.7</td>
<td></td>
</tr>
</tbody>
</table>

| Groundwater layer | 6.0x10⁻⁶ | 10 |
| Caprock | 0.25x10⁻⁶ | 5 |
| Basement rock | 0.25x10⁻⁶ | 5 |
| Upper reservoir layer low permeability case | 3.5x10⁻⁶ | 6 |
| Lower reservoir layer low permeability case | 3.5x10⁻⁶ | 5 |
| Upper reservoir layer intermediate permeability case | 17.5x10⁻⁶ | 6 |
| Lower reservoir layer intermediate permeability case | 17.5x10⁻⁶ | 6 |

Relative Permeability

Linear Curves, SIR : 0.30, SWR : 0.05, SWP : 0.70

<table>
<thead>
<tr>
<th>Well Parameters</th>
<th>Separator Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productivity index, m³·bar⁻¹·day⁻¹</td>
<td>Pressure, bar-a : 8.0</td>
</tr>
<tr>
<td>Pressure at upper layer, bar-a : 30.0</td>
<td>Temperature, °C : 170.4</td>
</tr>
<tr>
<td>Reinjection enthalpy, kJ/kg : 721.0</td>
<td></td>
</tr>
</tbody>
</table>
Figure 2-4 shows the areal grid structure of the model used in the present study and geometric locations of the production and injection wells. The model covers the same area as the Sigurdsson model but the grid structure used is regular and finer. It consists of a uniform grid of 24x30 elements all of size 66.7m x 66.7m. The vertical layer structure of the basic model used in this study is the same as in the Sigurdsson model.

![Figure 2-4 Grid structure showing the locations of the production wells (red) and injection wells (blue).](image)

In the Sigurdsson model the embedded radial grid consists of two concentric cylinders, the inner with radius 20m and the outer with radius 50m and thus the element size of our grid is not much larger than the outer element of the embedded grid.

As can be seen from Figure 2-4, a dipole configuration was used for the location of the wells, with injection in the north of the reservoir and the production in the south. Sigurdsson *et al.* (1995) considered additional injection and production
arrangements, but as the aim of this study is to test the effect of recharge assumptions only one reinjection strategy is considered here. For the models used in this study, the wells are located in the element at centre of the corresponding element in the Sigurdsson model.

A deliverability model (DELV) (autough2 (2008)) that allows for a declining flow rate with time as the reservoir is depleted is used for all production wells. For the DELV option, production occurs against a specified wellbore pressure. This option allows for the representation of wells that are completed in more than one layer. The mass production rate from each feed zone of a production well is given by the following formula,

\[ q_m = PI \frac{k}{\nu_f} (p - p_{wb}) \]  

Where \( q_m \) is the mass flow, \( PI \) is the productivity index, \( k \) is the absolute permeability, \( \nu \) is the kinematic viscosity of the reservoir fluid, \( p \) is the reservoir pressure, \( p_{wb} \) is the well-bore pressure at the layer in which the well is open. For multiple feed wells \( p_{wb} \) is specified at the top layer and then the well-bore pressure at the other feeds is calculated by TOUGH2 (see Pruess et al. (1999)).

Five production wells are used, each open in both reservoir layers. For the cases where reinjection is included the same flow rate is used for all injection wells, assumed to be open only in the upper reservoir layer.

The exploitation period is 60 years. The separator pressure is set at 8 bar-a.

Sigurdsson et al. (1995) and Sigurdsson and Stefansson (1998) assumed that the top and base of their model is closed. They considered two cases for lateral boundary conditions, either closed or open. The main purpose of the present study is to investigate the effect of more general boundary conditions, with vertical recharge possible at the top and base of the model as well as lateral recharge from the sides.
Chapter 2. Icelandic Models

As mentioned above one problem with the Sigurdsson model is that it has closed boundary conditions at the top and base of the model. These boundary conditions make it impossible to determine the effect of cold recharge from above or hot recharge from below. Furthermore with no vertical through-flow of heat and mass the initial temperatures and pressures are not in an equilibrium state. In order to investigate vertical recharge a more complex vertical structure has to be considered. In the present study an open top boundary is used and a small inflow of hot water is injected at the base of the model to establish an equilibrium state close to the initial conditions used with the Sigurdsson model.

Table 2-3 shows the catalogue of the models discussed in this chapter. The specifications of these models are summarised in Table 2-4.

Table 2-3  Catalogue of models

<table>
<thead>
<tr>
<th>Model</th>
<th>Areal grid</th>
<th>Sub-grid</th>
<th>Initial conditions</th>
<th>boundary condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Top</td>
</tr>
<tr>
<td>Model 1</td>
<td>66 blocks most of size 200m x 200m</td>
<td>2 radial blocks</td>
<td>specified in Table 2-1</td>
<td>closed</td>
</tr>
<tr>
<td>Model 2a</td>
<td>720 blocks each 66.7m x 66.7m</td>
<td>none</td>
<td>specified in Table 2-1</td>
<td>closed</td>
</tr>
<tr>
<td>Model 2b</td>
<td>720 blocks each 66.7m x 66.7m</td>
<td>none</td>
<td>specified in Table 2-1</td>
<td>open</td>
</tr>
<tr>
<td>Model 3</td>
<td>720 blocks each 66.7m x 66.7m</td>
<td>none</td>
<td>1D-natural state</td>
<td>open</td>
</tr>
</tbody>
</table>
| Model 4 | 1266 blocks (reservoir each 66.7m x 66.7) | none | 1D-natural state and adjusted conditions for lateral blocks | open | flow of hot water | open recharge
a) none
b) hot
c) hot
d) cold
e) infinite |
| Model 5 | 720 blocks each 66.7m x 66.7m | none | 1D-natural state | open | Additional basement layers + flow of hot water | closed |
| Model 6 | 720 blocks each 66.7m x 66.7m | none | 1D-natural state | open | flow of hot water | closed |
| Model 7 | 720 blocks each 66.7m x 66.7m | none | 1D-natural state | open | flow of hot water | closed |
| Model 8 | 720 blocks each 66.7m x 66.7m | none | 1D-natural state | open | flow of hot water | closed |
## Table 2-4 Specifications of the models

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
<th>Areal grid</th>
<th>Vertical grid</th>
<th>Model depth, m</th>
<th>Model area, m²</th>
<th>Initial conditions</th>
<th>Top Boundary conditions</th>
<th>Base Boundary conditions</th>
<th>Lateral boundary conditions</th>
<th>Extra features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>Sigurdsson model</td>
<td>66 blocks most of size 200m x 200m</td>
<td>4-layer</td>
<td>1400</td>
<td>1600x2000</td>
<td>specified in Table 2-1</td>
<td>closed</td>
<td>closed</td>
<td>closed</td>
<td></td>
</tr>
<tr>
<td>Model 2a</td>
<td>Model 1 + A fine grid structure</td>
<td>720 blocks each 66.7m x 66.7m</td>
<td>4-layer</td>
<td>1400</td>
<td>1600x2000</td>
<td>specified in Table 2-1</td>
<td>closed</td>
<td>closed</td>
<td>closed</td>
<td></td>
</tr>
<tr>
<td>Model 2b</td>
<td>Model 2a + Open top boundary</td>
<td>720 blocks each 66.7m x 66.7m</td>
<td>4-layer</td>
<td>1400</td>
<td>1600x2000</td>
<td>specified in Table 2-1</td>
<td>open</td>
<td>closed</td>
<td>closed</td>
<td></td>
</tr>
<tr>
<td>Model 3</td>
<td>Model 2b + 1D-natural state initial condition</td>
<td>720 blocks each 66.7m x 66.7m</td>
<td>4-layer</td>
<td>1400</td>
<td>1600x2000</td>
<td>specified in Table 2-5</td>
<td>open</td>
<td>flow of hot water</td>
<td>closed</td>
<td></td>
</tr>
<tr>
<td>Model 4</td>
<td>Model 3 + lateral recharge blocks</td>
<td>1266 blocks (reservoir blocks 66.7m x 66.7m)</td>
<td>4-layer</td>
<td>1400</td>
<td>4000x4400</td>
<td>reservoir: specified in Table 2-5</td>
<td>open</td>
<td>flow of hot water</td>
<td>open</td>
<td>Permeability of outer zone: kx=ky=kz=43% less than reservoir</td>
</tr>
<tr>
<td>Model 4a</td>
<td>Model 4+ (Hot outer zone – no recharge)</td>
<td>1266 blocks (reservoir blocks 66.7m x 66.7m)</td>
<td>4-layer</td>
<td>1400</td>
<td>4000x4400</td>
<td>outer zone: specified in Table 2-5</td>
<td>open</td>
<td>flow of hot water</td>
<td>open</td>
<td>Permeability of outer zone: kx=ky=1.0E-20 m² kx=ky=43% less than reservoir</td>
</tr>
<tr>
<td>Model 4b</td>
<td>Model 4+ (Hot outer zone – hot recharge)</td>
<td>1266 blocks (reservoir blocks 66.7m x 66.7m)</td>
<td>4-layer</td>
<td>1400</td>
<td>4000x4400</td>
<td>outer zone: specified in Table 2-5</td>
<td>open</td>
<td>flow of hot water</td>
<td>open</td>
<td>Permeability of outer zone: kx=ky=kz=43% less than reservoir</td>
</tr>
<tr>
<td>Model 4c</td>
<td>Model 4+ (Hot outer zone – hot recharge)</td>
<td>1266 blocks (reservoir blocks 66.7m x 66.7m)</td>
<td>4-layer</td>
<td>1400</td>
<td>4000x4400</td>
<td>outer zone: specified in Figure 2-16</td>
<td>open</td>
<td>flow of hot water</td>
<td>open</td>
<td>Permeability of outer zone: kx=ky=kz=43% less than reservoir</td>
</tr>
<tr>
<td>Model 4d</td>
<td>Model 4+ (Warm outer zone – hot recharge)</td>
<td>1266 blocks (reservoir blocks 66.7m x 66.7m)</td>
<td>4-layer</td>
<td>1400</td>
<td>4000x4400</td>
<td>outer zone: specified in Figure 2-16</td>
<td>open</td>
<td>flow of hot water</td>
<td>open</td>
<td>Permeability of outer zone: kx=ky=kz=43% less than reservoir</td>
</tr>
<tr>
<td>Model 4e</td>
<td>Model 4+ (Warm outer zone – hot recharge from infinite boundary)</td>
<td>1266 blocks (reservoir blocks 66.7m x 66.7m)</td>
<td>4-layer</td>
<td>1400</td>
<td>4000x4400</td>
<td>outer zone: specified in Figure 2-16</td>
<td>open</td>
<td>flow of hot water</td>
<td>open</td>
<td>Permeability of outer zone: kx=ky=kz=43% less than reservoir</td>
</tr>
<tr>
<td>Model 5</td>
<td>Model 3 + deeper layers</td>
<td>720 blocks each 66.7m x 66.7m</td>
<td>9 layer</td>
<td>3400</td>
<td>1600x2000</td>
<td>1D natural state from (9-Layer)</td>
<td>open</td>
<td>flow of hot water</td>
<td>closed</td>
<td>Table 2-10 shows reservoir, basement rock and cap-rock permeabilities for Model 5a,b,c,d,e,f,g</td>
</tr>
<tr>
<td>Model 6</td>
<td>Model 3 + vertically discretized</td>
<td>720 blocks each 66.7m x 66.7m</td>
<td>4-layer</td>
<td>1400</td>
<td>1600x2000</td>
<td>specified in Table 2-5</td>
<td>open</td>
<td>flow of hot water</td>
<td>closed</td>
<td>Model 6a and Model 6b scheme (a) and (b) in Figure 2-35</td>
</tr>
<tr>
<td>Model 7</td>
<td>Model 6 + nonuniform permeability</td>
<td>720 blocks each 66.7m x 66.7m</td>
<td>4-layer</td>
<td>1400</td>
<td>1600x2000</td>
<td>specified in Table 2-5</td>
<td>open</td>
<td>flow of hot water</td>
<td>closed</td>
<td>$k_{mean} = 4k_{mean}$ Model 7a and Model 7b scheme (a) and (b) in Figure 2-35</td>
</tr>
<tr>
<td>Model 8</td>
<td>Model 6 + nonuniform permeability</td>
<td>720 blocks each 66.7m x 66.7m</td>
<td>4-layer</td>
<td>1400</td>
<td>1600x2000</td>
<td>specified in Table 2-5</td>
<td>open</td>
<td>flow of hot water</td>
<td>closed</td>
<td>$k_{mean} = 11k_{mean}$ Model 8a and Model 8b scheme (a) and (b) in Figure 2-35</td>
</tr>
</tbody>
</table>
The following steps were carried out:

1- First the results for Sigurdsson’s closed (no lateral recharge) dipole model were reproduced (Model 1). Then a finer grid system was adopted for the next model (Model 2a).

2- Model 2a, with a closed top and closed base, was used as the base model. Next atmospheric conditions were implemented at the upper boundary (called Model 2b).

3- A natural state was derived for a 1D column model with an input of heat and mass at the base and atmospheric conditions at the top. This model was used to obtain a best fit temperature and pressure profile to those used for the Sigurdsson model.

4- Next the 1-D natural state initial conditions were implemented instead of the initial conditions used by Sigurdsson and small inputs of heat and mass were injected at the base. (Model 3)

5- Model 3 was then extended to test the effect of lateral recharge by adding an outer zone outside the reservoir and by allowing pressure dependent recharge through the outer boundary of the model (Model 4). Various options for the temperature of the outer zone and the reservoir permeability were investigated.

6- Again Model 3 was used as the base model and extra layers were added to the bottom of the model in order to represent the deep zone below the reservoir (Model 5). The effects of deep and shallow vertical recharge were investigated by varying the permeabilities of the cap rock and basement rock. In each case the appropriate initial conditions were taken from 1D column models.

7- The effect of vertical discretization on the model results was tested by refining Model 3 vertically (Model 6).

8- Model 7 and Model 8 were introduced with variations on Model 6 (the vertically discretized model), including feed zones with non-uniform permeability in some reservoir layers.
2.3 Results

2.3.1 The Sigurdsson Model

First, as a reference, a model with exactly the same grid structure as the Sigurdsson model was set up (called Model 1). The only difference between this model and the original Sigurdsson model is the treatment of the radial subgrid. In the Sigurdsson model the volume of the two radial blocks that were embedded into each production gridblock was not subtracted from the total volume of the gridblock. Whereas in Model 1, our version of the Sigurdsson model, the volume of the subgrid is subtracted from the block in which it is embedded. Model 1 was run with the same initial and boundary conditions as the Sigurdsson model. The intermediate reservoir permeability case was investigated with the rock parameters as listed in Table 2-2 and the dipole injection and production configuration was used. This corresponds to Case II in Sigurdsson et al. (1995). The same three levels of reinjection of 0, 130 and 215kg/s were used here. The results for the steam production rate over 60 years of production are shown in Figure 2-5.

![Figure 2-5 Steam production rates for the original Sigurdsson model and Model 1.](image_url)
Good agreement with Sigurdsson’s results was obtained for the no-injection case and the low-injection case (130kg/s). The differences are easily explained in terms of the slightly different grid structure. However for the high-injection case (215kg/s) the results do not agree. The reasons for this are not clear. It was possible to obtain good agreement with all other results shown by Sigurdsson et al. (1995), but it was only possible to approximately match the graph for the case of 215kg/s injection shown in Figure 2-5 if different (open rather than closed) boundary conditions were used.

We next switched to the finer grid shown in Figure 2-4 (Model 2). The effect of the finer grid used in Model 2 was tested by running the same Case II from Sigurdsson et al. (1995). The results in Figure 2-6 show good agreement with those from the Sigurdsson model, thus verifying that our fine grid model is equivalent to the coarse grid with an embedded sub-grid used by Sigurdsson et al. (1995).

![Figure 2-6 Comparison of results from our version of the Sigurdsson model (Model 1) and the fine grid model (Model 2a).](image-url)
2.3.2 Initial temperature and pressure profiles

As mentioned above the initial conditions used in the Sigurdsson model, without any input of heat and mass at the base, are not in equilibrium. To check the stability of the system with these initial conditions, our fine grid model was run for 60 years without production and injection. Figure 2-7 shows that over 60 years the temperatures of the system do not change much, however there are significant pressure changes, especially in the upper layers of the system (Figure 2-8). When the model was run for very long time, as a natural state model, the pressure and temperature distribution of the system changes entirely. Therefore the Sigurdsson model is not in a steady state, and this may have an effect on steam production over 60 years. Thus it was decided to develop an alternative version of the Sigurdsson model, with initial conditions as close as possible to those used by Sigurdsson et al. (1995), but with open top boundary conditions and with pressure and temperatures in equilibrium with a small through flow of heat and mass. This model is called Model 3.

![Figure 2-7](image)

Figure 2-7 Temperature changes after 60 years, without production and injection, using Model 2a.
There are two reasons for modifying the top and bottom boundary conditions and the initial conditions from those used in the Sigurdsson model:

(i) In order to investigate the communication of the reservoir with the groundwater aquifers it is necessary to use open boundary conditions at the top of the model.

(ii) To investigate the effect of deep recharge it is necessary to extend the model vertically. Some vertical refinement of the model may also be desirable. Thus it is necessary to be able to choose initial conditions for a vertically refined deeper model.

To do this it was decided to set up a 1D vertical model to obtain natural state conditions as close as possible to Sigurdsson’s initial conditions and in equilibrium with suitable vertical flows of heat and mass.

Three different 1D vertical models with different vertical structures were developed, some to be used at later stages of this study. Atmospheric conditions are maintained at the ground surface (p= 1 bar, T= 5°C). Each model is 200m x 200m in areal extent and has layers representing the groundwater, cap-rock, upper reservoir and lower reservoir. The third model has additional layers to represent the basement rock. The rock parameters used for these models are the same as for
the Sigurdsson model (see Table 2-2). The intermediate reservoir permeability (17.5E-15m²) case was used for the models presented here. The basement rock parameters used are similar to the cap-rock parameters.

a) Four-layer model, down to 1400m depth:

This model has the same layer structure as the Sigurdsson model with four layers representing groundwater (300m), cap-rock (300m), upper reservoir (400m) and lower reservoir (400m), respectively. The inverse modelling code iTOUGH (Finsterle (2000)) was used to obtain a good fit to the required temperature and pressures, giving a best-fit value for the mass flow at the base of the model of 0.028kg/s at an enthalpy of 1775.0kJ/kg.

Table 2-5 shows the pressure and temperature values which were obtained from the four-layer 1D vertical natural state model and the initial conditions used by Sigurdsson et al. (1995) for near two-phase conditions

**Table 2-5 Initial conditions for the four-layer 1D vertical model.**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Pressure, bar</th>
<th>Temperature, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groundwater</td>
<td>15.523</td>
<td>92.125</td>
</tr>
<tr>
<td>Cap rock</td>
<td>43.058</td>
<td>204.99</td>
</tr>
<tr>
<td>Upper reservoir</td>
<td>71.225</td>
<td>282.18</td>
</tr>
<tr>
<td>Deeper reservoir</td>
<td>99.435</td>
<td>310.54</td>
</tr>
</tbody>
</table>

Figure 2-9 shows the comparison of these temperature and pressure profiles for a four-layer 1D vertical model with those from Sigurdsson et al. (1995).
b) Fourteen-layer model down to 1400m depth;

This model has fourteen layers, each 100m thick, representing groundwater (3 layers), cap-rock (3 layers), the upper reservoir (4 layers), and the lower reservoir (4 layers). Inverse modelling with iTOUGH2 gave the best-fit values for the input at the base of the models of a mass flow of 0.0287kg/s and an enthalpy of 1635kJ/kg.

Figure 2-10 shows the comparison of the temperature and pressure profiles which were obtained from the fourteen-layer 1-D vertical natural state model and the initial conditions used by Sigurdsson et al. (1995).
c) Deeper model, 9 layers down to 3400m depth;

For this model five basement layers (each 400m thick) were added below the four-layer model. The input at the base of this model was the same as for the four-layer model.

Figure 2-11 shows the comparison of temperature and pressure profiles which are obtained from the 9 layer 1-D vertical natural state model and initial conditions used by Sigurdsson et al. (1995).

The pressure values obtained from the three different 1D vertical models, and for the original Sigurdsson model, are just above the boiling point in the reservoir layers, i.e. in its initial state the reservoir is just about to boil. The pressures from the 1D model are a little higher than those used by Sigurdsson.

![Figure 2-11 Temperature and pressure profiles from Sigurdsson et al. (1995) and from the 9 layer 1D vertical model.](image)

At later stages of the study, in order to investigate downward flow of the groundwater and deep recharge, different permeabilities for the cap-rock and the basement rock were tested. To obtain the initial conditions that match the initial conditions of the Sigurdsson model (Table 2-1) for these cases, new 1D vertical models were set up including the corresponding permeability changes. Thus the 1D vertical models discussed above were also run for the low permeability (3.5E-15m²) reservoir case in order to produce suitable steady state initial conditions.
Table 2-6 shows various reservoir, cap-rock and basement permeabilities and heat and mass input applied at the base of these models. As can be seen from this table the same amount of mass with same enthalpy is applied at the base of all of the 9 layer 1D models. Changing the permeability of the cap-rock and the basement rock changed the pressure and temperature values in the basement layers, but did not have a discernible effect on the upper and lower reservoir layers or on the groundwater and the cap-rock layers (see Figure 2-12).

Table 2-6  1D model parameters. Permeabilities for reservoir, cap-rock and base. Heat and mass input values.

<table>
<thead>
<tr>
<th>1D model</th>
<th>Permeabilities x10^-15</th>
<th>Input (for 200mx200m grid)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>reservoir</td>
<td>cap-rock</td>
</tr>
<tr>
<td>4 layer-1400m</td>
<td>17.5</td>
<td>.25</td>
</tr>
<tr>
<td>4 layer-1400m</td>
<td>3.5</td>
<td>.25</td>
</tr>
<tr>
<td>14 layer-1400m</td>
<td>17.5</td>
<td>.25</td>
</tr>
<tr>
<td>9 layer-3400m</td>
<td>17.5</td>
<td>.25</td>
</tr>
<tr>
<td>9 layer-3400m</td>
<td>17.5</td>
<td>.25</td>
</tr>
<tr>
<td>9 layer-3400m</td>
<td>17.5</td>
<td>.25</td>
</tr>
<tr>
<td>9 layer-3400m</td>
<td>17.5</td>
<td>.25</td>
</tr>
<tr>
<td>9 layer-3400m</td>
<td>3.5</td>
<td>.25</td>
</tr>
<tr>
<td>9 layer-3400m</td>
<td>17.5</td>
<td>.50</td>
</tr>
<tr>
<td>9 layer-3400m</td>
<td>17.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Figure 2-12  Pressure and temperature profiles for the deeper model (9 layer-3400m depth)
2.3.3 Top and bottom boundary conditions

First the effect of using an open top boundary condition (constant temperature and pressure) was investigated. This was implemented by assigning a very large atmosphere blocks at the top of the model, to represent a wet atmosphere at the top boundary. This model is called Model 2b. The original initial conditions used by Sigurdsson et al. (1995), were used for both Model 2a and Model 2b. The results in Figure 2-13 show a small effect, which is not unexpected given the very low permeability of the cap-rock (0.25E-15m²).

![Figure 2-13 Comparison of results for Model 2b (open top - lines) and Model 2a (closed top - symbols).](image)

Next the effect of introducing an initial state in equilibrium with a vertical heat and mass through-flow (determined from the 1-D vertical model) was investigated (Model 3). For the two cases shown in Figure 2-14, both models (Model 2b and Model 3) have an open boundary at the top of the model, implemented by using a large volume atmosphere block, whereas the original Sigurdsson model had a closed top and no-atmosphere block. As shown in Figure 2-14 the modified initial state does not significantly affect the steam production rates. The only noticeable difference between Model 2b and Model 3 is the behaviour between 20-25 years, with an early drop of steam production for Model 3, for the no-reinjection case.
The reason for these differences is that the initial conditions used by Sigurdsson are closer to the boiling curve.

![Figure 2-14. Steam production rates for Model 3 (steady state initial conditions - symbols) and Model 2b (Sigurdsson’s initial conditions - lines).](image)

### 2.3.4 Lateral recharge

To explore the effect of lateral recharge, the grid used for Models 1-3 was enlarged by adding an outer zone 1.2km wide. This model is called Model 4. The grid structure of Model 4 is shown in Figure 2-15. The red area in this figure is the grid used for Models 1-3, and the surrounding area shows the enlarged section. This is the same area introduced by Sigurdsson et al. (1995) as a recharge area. These authors did not give details of the grid structure they used in the outer zone but there is an implication that it was only one element wide. As shown in Figure 2-15 the areal grid structure used here is more complex, thus allowing for more accurate representation of the lateral inflow.
Additionally Sigurdsson et al. (1995) considered effectively infinite boundaries by using a recharge zone 6km wide. We also consider an equivalent model by allowing recharge boundary conditions at the outside of the 1.2km outer zone. The mass flow into the boundary blocks is given by the formula

\[ q_m = A(p - p_o) \]  \hspace{1cm} (2-2)

Here \( q_m \) is the mass flow, \( A \) is the recharge coefficient, \( p \) is the block pressure and \( p_o \) is the initial block pressure. The recharge coefficient values depend on the size and permeability of the outermost gridblock. The values of recharge coefficient for most of the blocks for each layer are given in Table 2-7. The flow can be either into or out of the boundary block. If it is an inflow the enthalpy is assumed to be at the original block value corresponding to the initial state \( p_o, T_o \).
Table 2-7 The recharge coefficient values for each layer

<table>
<thead>
<tr>
<th>Layer</th>
<th>A, m^3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground water</td>
<td>2.13E-06</td>
</tr>
<tr>
<td>Cap-rock</td>
<td>1.89E-07</td>
</tr>
<tr>
<td>Upper reservoir</td>
<td>2.98E-05</td>
</tr>
<tr>
<td>Deeper reservoir</td>
<td>4.22E-05</td>
</tr>
</tbody>
</table>

As in real reservoirs lateral recharge is important. In the Sigurdsson model the outer zone was assumed to be at the same temperature and pressure as the interior zone (O. Sigurdsson, private communication). We consider the additional case where the outer zone is warm rather than hot. The temperatures used are shown in Figure 2-16.

Figure 2-16. Grid structure and initial temperature distribution for the cold recharge models (Model 4d and Model 4e)

Because the temperature gradient in geothermal areas can be up to 200°C/km or more (Garcia-Estrada et al. (2001)), we assumed a temperature gradient for the outermost area (area 4 shown with light blue) of 150°C/km. The blue line in Figure 2-16 corresponds to the temperature vs depth profile in this area. For area 1 in Figure 2-16, the temperature profile is the same at that used by Sigurdsson and Stefansson (1998) for a hot water reservoir (orange plot). For areas 2 and 3 the temperature values were obtained by interpolation between the temperature profiles.
Chapter 2. Icelandic Models

for areas 1 and 4. The dark red curve in this plot corresponds to the reservoir temperatures (also shown in Table 2-5).

There are many possible cases to consider, allowing for variations in the permeability, temperature distribution and boundary conditions for the outer zone. Here only five representative cases are considered (see Table 2-8).

Table 2-8 Recharge Models

<table>
<thead>
<tr>
<th>Model</th>
<th>Outer zone</th>
<th>Recharge condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Extension</td>
<td>Permeability</td>
</tr>
<tr>
<td>Model 4a</td>
<td>1.2 km</td>
<td>lateral=1.0E-20m²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>vertical=43% less than reservoir</td>
</tr>
<tr>
<td>Model 4b</td>
<td>1.2 km</td>
<td>43% less than reservoir</td>
</tr>
<tr>
<td>Model 4c</td>
<td>1.2 km</td>
<td>lateral=43% less than reservoir</td>
</tr>
<tr>
<td></td>
<td></td>
<td>vertical=1/1x10⁻⁵ of lateral</td>
</tr>
<tr>
<td>Model 4d</td>
<td>1.2 km</td>
<td>lateral=43% less than reservoir</td>
</tr>
<tr>
<td></td>
<td></td>
<td>vertical=1/1x10⁻⁵ of lateral</td>
</tr>
<tr>
<td>Model 4e</td>
<td>Effectively infinite</td>
<td>43% less than reservoir</td>
</tr>
</tbody>
</table>

The term “interior recharge” is used to describe the flow within the model from the outer zone into the reservoir zone, whereas “exterior recharge” is used to describe the flow through the boundary of the outer zone when recharge boundary conditions are implemented using (2-2).

As is shown in Table 2-3, an open top boundary is used in all cases for Model 4. The natural state initial conditions that were used in Model 3 are used for Model 4 also. As for Model 3, a constant flow of hot water at the base of the system is assigned for Model 4.

A) Model 4a, Hot outer zone, no interior recharge and no exterior recharge: First the conductive effect of the hot outer zone was tested by assigning a very low value (1.0E-20m²) for the lateral permeability of boundary blocks. For this case the
initial conditions for the boundary blocks were chosen to be the same as for the reservoir blocks. As expected Figure 2-17 shows there is no effect from the hot outer zone of the system if the surrounding rock is not permeable.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure2-17.png}
\caption{Steam production rates for the laterally closed model (Model 3) and for the extended model with a very low permeability in the outer zone (Model 4a).}
\end{figure}

B) Model 4b, hot interior recharge, no exterior recharge: In this case the initial temperatures and pressures in the outer zone are set to be the same as in the neighbouring reservoir blocks. Following Sigurdsson et al. (1995), the permeability of the outer zone was set to be $1.995 \times 10^{-15} \text{m}^2$ and $9.975 \times 10^{-15} \text{m}^2$ for low and intermediate permeability cases, respectively, i.e. 43% less than the value for the reservoir blocks.

As can be seen from Figure 2-18, in all cases Model 4b produces much more steam than Model 3. This indicates that a considerable amount of recharge comes from the large outer zone blocks. Therefore hot recharge is important with respect to steam production. Figure 2-18 shows if there is hot recharge from the boundary blocks, the effect of reinjection is small, as the steam production rates are quite close to each other. This figure also shows that if recharge is hot, then reinjection
decreases steam production, and in the long term the no-injection case produces the highest amount of steam.

![Figure 2-18 Steam production rates for the closed model (Model 3) (symbols) and hot interior recharge model (Model 4b) (lines).](image)

The vertical connection between the outer zone blocks allows up-flow and down-flow between the layers in these zones and this may lead to a recharge into the reservoir at a different temperature from the initial state. To investigate the importance of this effect another model was set up with a low vertical permeability in the recharge blocks (5 orders of magnitude smaller than the lateral permeability) to allow the observation of the effect of hot lateral recharge alone. This new model is named Model 4c. Model 4c was also run for 60 years of production for no-reinjection and reinjection of 130kg/s and 215kg/s. The results from Model 4c (not shown) are not significantly different to those for Model 4b.

C) Model 4d, warm interior recharge, no exterior recharge: To examine the effect of having a cooler lateral recharge it was assumed that the temperature of the surrounding blocks gradually decreases from the hot reservoir temperature to a temperature profile that has a gradient of 0.15°C/m. To obtain such a model the outer zone was divided into four sub-regions each with a different temperature
profiles (Figure 2-16). The initial pressures in the outer zone blocks are the same as in the neighbouring reservoir blocks. The lateral permeability of the large boundary blocks was set to be 43% less than the value for the reservoir blocks. Again in this case the vertical permeability of the recharge blocks was chosen small enough (5 orders of magnitude smaller than the lateral permeability) to allow the observation of the effect of lateral recharge alone.

Because of the warm outer zone the initial state used in this model is not in stable equilibrium, as was also the case for the original Sigurdsson model. To check the stability of Model 4d, it was run for 60 years without production and injection. The results of these runs showed that temperature and pressure distributions for the model do not change over 60 years for the reservoir area (orange area in Figure 2-16) and for the outermost area (area 4, shown with light blue in Figure 2-16). The maximum temperature changes at the transition blocks (area 1, 2 and 3 in Figure 2-16) are shown in Table 2-9. Much greater changes in temperatures and pressures are observed if the vertical permeability in the outer zone is not reduced.

Since, without production and injection, the temperature of the reservoir does not change over 60 years, Model 4d is considered to be suitable for a 60 year simulation.

Table 2-9 Maximum temperature changes in the outer zone over 60 years for Model 4d

<table>
<thead>
<tr>
<th>Layer</th>
<th>Temperature changes, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>ground</td>
<td>-2 and +1</td>
</tr>
<tr>
<td>cap-rock</td>
<td>-5 and +2</td>
</tr>
<tr>
<td>Upper reservoir</td>
<td>-7 and +5</td>
</tr>
<tr>
<td>Lower reservoir</td>
<td>-12 and +8</td>
</tr>
</tbody>
</table>

Figure 2-19 compares the steam production rates for Model 4d (warm interior recharge, no exterior recharge) with those for Model 3 (closed model with no outer zone). The two sets of results are remarkably similar, showing that with the warm outer zone the effect of lateral recharge to the system is very small.
Figure 2-19  Steam production rates for the closed model (Model 3) (symbols) and warm interior recharge model (Model 4d) (lines).

The temperature distributions in the cap-rock, upper reservoir and lower reservoir layers are shown in Figure 2-20, Figure 2-21 and Figure 2-22, respectively, for the no-reinjection and 130kg/s and 215kg/s reinjection cases after 60 years of production. According to these figures, if there is no reinjection the temperature in the lower production area decreases due to the cold inflow from the lateral boundaries of the system. Reinjection decreases the reservoir temperature at the reinjection area but prevents the temperature drop at the production area because it prevents cold water inflow from the sides of the system. Increasing the reinjection rate from 130kg/s to 215kg/s increases the invasion of cold reinjection water into the reservoir, and hence the temperature at the production area decreases.
Figure 2-20 Temperature distributions at the cap-rock layer for: (a) 0kg/s, (b) 130kg/s and (c) 215kg/s for Model 4d (warm interior recharge).

Figure 2-21 Temperature distributions at the upper reservoir layer for: (a) 0kg/s, (b) 130kg/s and (c) 215kg/s for Model 4d (warm interior recharge).

Figure 2-22 Temperature distributions at the lower reservoir layer for: (a) 0kg/s, (b) 130kg/s and (c) 215kg/s for Model 4d (warm interior recharge).
The effect of lateral recharge on steam production depends on the communication between the production zone and the surrounding zone. Therefore the low and intermediate reservoir permeability cases were also examined to test the effect of reservoir permeability on lateral cold recharge (see Table 2-2). Figure 2-23 shows that while a low permeability reservoir produces a smaller amount of steam at early times, for the intermediate permeability reservoir the steam production drops more quickly and after about 30 years the results become similar for both cases. There is no remarkable difference in the effect of reinjection for the two sets of results.

![Figure 2-23](image_url)

**Figure 2-23** Steam production rates for the warm interior recharge model (Model 4d) with low and medium reservoir permeability.

**D) Model 4e, warm interior recharge, cold exterior recharge:** To examine the effect of a stronger lateral recharge, an effectively infinite outer zone was implemented by using recharge boundary conditions at the boundary of the outer zone of the extended model. The initial conditions that were used with Model 4d were used again in this case. In this case to obtain equivalent recharge to the infinite boundary model used by Sigurdsson *et al.* (1995), recharge wells were assigned to the outermost blocks by using the RECH option (autough2 (2008)). The mathematical formula for this option is given in Equation (2-2). The RECH option used here allows extra recharge to enter the system through the side
boundaries, in proportion to the pressure drop. This option also keeps the enthalpy of the recharge fluid the same as the initial enthalpy. So that if the block is initially cold, then cold fluid enters the system.

Figure 2-24 compares the steam production rates for Model 4d with those for Model 4e. This figure shows for the cases where the reservoir has strong cold recharge from the outer boundaries, steam production significantly increases. This figure shows that, even with a 1.2km extension, a closed model will give an under-estimate of the steam flow and an over-estimate of the effect of reinjection. If there is enough recharge then the reservoir pressure does not drop as much which maintains the steam flow at a higher level. In the long term, injection does not cause a significant increase in steam production.

![Figure 2-24 Steam production rates for Model 4d (no exterior recharge) and Model 4e (exterior recharge).](image)

The temperature distributions in the upper reservoir and lower reservoir layers are shown in Figure 2-25 and Figure 2-26, respectively, for the no-reinjection and 130kg/s and 215kg/s reinjection cases after 60 years of production. According to these figures, if there is no reinjection, the temperature of the production area decreases significantly after 60 years of production due to the warm lateral recharge. Reinjection results in less warm lateral recharge to the reservoir because
it supports the reservoir pressures. However the breakthrough of reinjection fluid to the production zone decreases the reservoir temperature. Thus the higher rate of reinjection increases the size of the zone that is invaded by the reinjection fluid and causes a larger temperature drop in the production area.

Comparison of Figure 2-25 and Figure 2-26 with Figure 2-21 and Figure 2-22 shows that if there is no-reinjection, at the end of 60 years of production, the temperatures in the surrounding blocks are lower for Model 4e (warm interior, cold exterior recharge) than for Model 4d (warm interior recharge, no exterior recharge). However the interior of the reservoir is at a higher temperature for Model 4e. This comparison indicates that stronger recharge from the side boundaries sweeps more heat from the outer zones into the reservoir, thus leading to a higher steam production. The results in Figure 2-24 show that having a closed boundary on a large recharge zone around the reservoir gives an over-estimate of the effect of reinjection.

Figure 2-25  Temperature distributions at the upper reservoir layer for: (a) 0kg/s, (b) 130kg/s and (c) 215kg/s for Model 4e (warm interior recharge, cold exterior recharge).
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2.3.5 Vertical recharge

To represent the natural upflow from the deeper part of the reservoir, 5 more layers each 400m thick were added beneath Model 3. The basement permeability for this model is 0.25E-15m², as shown in Table 2-2. The natural state conditions from the 9 layer 1D vertical model were used as the initial conditions and mass and heat inputs for this model (called Model 5a).

Figure 2-27 shows the comparison of steam production rates for the no-injection and two cases of reinjection for Model 5a and Model 3 (with and without the basement layer, respectively). As can be seen from Figure 2-27, a significant amount of hot recharge comes from the deeper part of the reservoir, enhancing the steam flow. While there is a big difference between the results for the no-reinjection and the high reinjection cases for Model 3, for the model which allows deep recharge (Model 5a) this difference is small. An increase in the reinjection rate causes only a small increase in steam flow.
To investigate the importance of vertical recharge, different vertical permeabilities were tried for both the cap-rock and the basement rock (see Table 2-10). For each case a 9 layer 1D vertical model was used to determine the initial conditions and mass and heat inputs of these new models. The basement and cap-rock permeability used for the deeper model (Model 5) are shown in Table 2-10.

**Figure 2-27 Steam production rates for the model with no basement (Model 3) and the model with a basement (Model 5a).**

**Table 2-10 Basement and cap-rock permeability for the deeper model (Model 5)**

<table>
<thead>
<tr>
<th>Model</th>
<th>Permeabilities, x10-15m²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reservoir</td>
</tr>
<tr>
<td>Model 5a</td>
<td>17.5</td>
</tr>
<tr>
<td>Model 5b</td>
<td>17.5</td>
</tr>
<tr>
<td>Model 5c</td>
<td>17.5</td>
</tr>
<tr>
<td>Model 5d</td>
<td>17.5</td>
</tr>
<tr>
<td>Model 5e</td>
<td>3.5</td>
</tr>
<tr>
<td>Model 5f</td>
<td>17.5</td>
</tr>
<tr>
<td>Model 5g</td>
<td>17.5</td>
</tr>
</tbody>
</table>
Chapter 2. Icelandic Models

2.3.5.1 Vertical permeability of the basement layer

Model 5a was chosen as the base model and three different values for the basement vertical permeability were tried, 0.025, 0.5 and 1.0E-15m², (Models 5b, 5c, 5d) (see Table 2-10).

Figure 2-28 compares results for Model 3 (with no basement layers), and Model 5b, with a very low (0.025E-15m²) vertical basement rock permeability. This figure shows that although the permeability of the basement rock is very low, if there is no reinjection the pressure decrease caused by production induces upflow from the base of the system and causes an increase in the steam production rate. But if there is injection to the field, this effect is very small and the effect of the deeper layers below the reservoir is negligible.

![Figure 2-28](image-url)  Steam production rates for Model 3 (symbols) and Model 5b (vertical permeability in the basement layer of 0.025 E-15m² - lines).

Figure 2-29 shows the effect of increasing the vertical permeability of the basement layer from 0.025E-15m² (Model 5b) to 0.25E-15m² (Model 5a). For all reinjection rates the increased permeability of the basement allows more deep hot recharge and thus a higher steam flow. However increased reinjection still increases the steam
flow although the effect is smaller i.e. there is a smaller difference between the case of no-injection and the case of reinjection of 215kg/s.

Figure 2-29 Steam production rates for the models with a vertical permeability in the basement of 0.025 E-15m² (Model 5b) (symbols) and 0.25E-15m² (Model 5a) (lines).

Figure 2-30 compares the results for Model 5a (0.25E-15m² basement permeability) with intermediate vertical permeability case (0.5E-15m²) (Model 5c). The plot shows that with the higher permeability of the basement rock the steam production rate is also higher. For Model 5c, the effect of reinjection on steam production is not significant. As shown in the plots, for Model 5c, reinjection does not have any effect on steam production for the first 25 years of production.
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Figure 2-30  Steam production rates for the models with a vertical permeability in the basement of 0.25E-15m² (Model 5a) and 0.5E-15m² (Model 5c).

Figure 2-31 compares the results for Model 5c with those for the case of a high (1.0E-15m²) vertical basement permeability (Model 5d). The plot shows that with the high basement permeability, the steam flow is much higher. For Model 5d injection does not increase steam flow, in fact the effect of reinjection changes qualitatively. The highest reinjection rate no longer produces the highest steam flow. Since the injected fluid is cooler than the recharge from the bottom of the system, increasing the reinjection rate decreases the reservoir temperature and causes a reduced steam production (Figure 2-31). However, at the very late stage of production (after about 50 years), the steam flow starts to drop faster for the no-reinjection case, while the high reinjection rate (215kg/s) results in a constant production rate of steam.
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2.3.5.2 Effect of varying reservoir permeabilities (for a high permeability basement).

In this section, the effect of reinjection on steam production is investigated for different reservoir permeabilities. Because the high permeability basement has the highest impact on steam production, at this stage we investigated how the results are affected if the permeability in the reservoir is decreased. Therefore Model 5d was taken as the base model and a low reservoir permeability case is implemented. This new model is called Model 5e.

Figure 2-32 compares the model results for cases of intermediate (17.5E-15m^2) and low (3.5E-15m^2) reservoir permeabilities (Model 5d and Model 5e, respectively) for the case of a high permeability (1.0E-15m^2) basement rock. The plot shows that, the low permeability reservoirs produce much less steam then intermediate permeability reservoir, although for the low permeability case the steam production decreases very slowly after about 5 years of production. For the low permeability reservoir, after about 40 years of production the intermediate and high rate reinjection cases show similar steam production rates.

Figure 2-31 Steam production rates for the models with a vertical permeability in the basement of 0.5E-15m^2 (Model 5c) and 1.0E-15m^2 (Model 5d).
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2.3.5.3 Effects of varying the vertical permeability of the cap-rock

To determine the effect of groundwater recharge to the system different vertical permeabilities for the cap-rock were tried. Model 5a was chosen as the base model with 0.25E-15m² basement permeability and 0.25E-15m² cap-rock permeability. Two different vertical permeabilities for the cap-rock were tried: 0.5E-15m² and 1.0E-15m² (Model 5f and Model 5g, respectively) (see Table 2-10). The results for Models 5a and 5f (the 0.25E-15m² and 0.5E-15m² cases) are compared in Figure 2-33 and for Models 5a and 5g (the 0.25E-15m² and 1.0E-15m² cases) in Figure 2-34.

The higher cap-rock permeability allows more groundwater recharge. Cold groundwater inflow decreases the enthalpy of the system and hence causes it to produce less steam. According to the Figure 2-33, after 45 years of production there is no difference on the steam production between the models with low (0.25E-15m²) vertical cap-rock permeability or with intermediate (0.5E-15m²) vertical cap-rock permeability.

Figure 2-32 Steam production rates for the models with low and intermediate reservoir permeabilities. The vertical permeability of the basement layer is 1.0E-15m² (Model 5d).
Even if the reservoir receives recharge from groundwater, as for Model 5f with intermediate cap-rock permeability, reinjection still supports the reservoir pressure and increases steam production.

![Graph showing steam production rates for Model 5a and Model 5f](image)

**Figure 2-33** Steam production rates for Model 5a (vertical cap-rock permeability 0.25E-15m²) (symbols) and Model 5f (vertical cap rock permeability 0.5E-15m²) (lines).

As can be seen in Figure 2-34 for the case of a high cap-rock permeability (1.0E-15m²) there is a higher steam production. For the high reinjection case after about 40 years of production the effect of groundwater recharge starts to disappear as shown by the fact that the system produces the same amount of steam independent of the cap-rock permeability. The same effect at a later time is seen for the other injection rates.
2.3.6 Other Effects

2.3.6.1 Vertical discretization

To check the effect of vertical discretization Model 3 (four-layer model, no-lateral recharge from sides, no-vertical recharge from bottom boundaries) was refined to fourteen layers each of 100m. Therefore the reservoir is represented by 8 layers. This new model is called Model 6. Figure 2-35 shows the new grid structure for the upper and lower reservoir formations. As shown in this figure layers 8 and 12 (shown with orange) are open to production. Two different schemes were tried for injection (shown with blue in Figure 2-35).

- Model 6a: injection into the middle of the reservoir (layer 10, Figure 2-35(a)),
- Model 6b: injection into the top of the reservoir (layer 8, Figure 2-35(b)).
Initial conditions from a fourteen-layer 1D vertical column natural state model were used as the initial conditions for the vertically refined model (Model 6a and Model 6b). The effect of vertical refinement is shown in Figure 2-36 (a) and (b). According to these figures, increasing the number of layer does not change the results significantly. And there is no visible difference between the case where injection is into the middle (Model 6a) or into the top of the reservoir (Model 6b). Figure 2-36 (a) and (b) show that vertical refinement smoothes out the changes in the steam flow.
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Figure 2-36 Steam production rates for the 4-layer model (Model 3) (symbols) and the 14-layer model (lines): (a) Model 6a and (b) Model 6b.
2.3.6.2 Non-uniform permeability

Many geothermal fields consist of fractured rocks and the feed zones in the wells may be comparatively narrow and of high permeability, thus providing fast flow paths between production and injection wells.

To simulate a fractured rock reservoir, non-uniform permeabilities were assigned to the upper and lower reservoir layers (shown in Figure 2-35). In each reservoir one layer was given a high permeability and the others a low permeability with the total permeability-thickness product remaining unchanged at 7.0E-12m³.

Two cases of non-uniform permeability were tried:

a) Model 7, Small permeability difference: Model 6 is taken as the base case for this model. As in Model 6, the schemes shown in Figure 2-35 (a) and (b) are applied to this model as well, and called Model 7a and Model 7b, respectively. In this model the permeability of the production layers (shown with orange colour in Figure 2-35) is 40.0E-15m² and the permeability of the other layers is 10.0E-15m² (k_{fracture} = 4k_{matrix}). Figure 2-37 (a) and Figure 2-37 (b) compare the steam production rates for the homogenous permeability model (Model 6) and the model (Model 7b) which has feed zones (non-uniform permeability) for the two different schemes shown in Figure 2-35. The results show that, the model which has non-uniform reservoir permeability (Model 7) gives a higher steam production rate for about the first 15 years than the model with homogeneous reservoir permeability (Model 6). However for the later stages of production the effect of the feed zone vanishes if there is no reinjection into the field. Injection increases steam production but not as much as for the homogenous model. Comparison of Figure 2-37 (a) and Figure 2-37 (b) shows that injection into middle of the reservoir (Model 7a) slightly increases steam production for the high reinjection case and there is no apparent difference between the cases where injection is into the middle of the reservoir or into the top of the reservoir.
Figure 2-37  Steam production rates for Model 6 (homogenous permeability) (lines) and Model 7 (non-uniform with a small permeability difference) (symbols).

b) Model 8, Intermediate permeability difference: Again Model 6 is taken as the base case for this model. As in Model 6, the schemes shown in Figure 2-35 (a) and (b) are applied to this model as well, and called Model 8a and Model 8b respectively. In this model the permeability of the production layers is 55.0E-15m² and the permeability of other layers is 5.0E-15m² ($k_{\text{fracture}} = 11 \times k_{\text{matrix}}$). Figure
2-38a and Figure 2-38b compare the steam production rates for the homogenous model (Model 6) with those for the model which has feed zones (Model 8) for scheme (a) and scheme (b) (Figure 2-35). The results show that at the early stages of production (during the first 15 years of production) the fractured model produces a higher steam rate. For the later times of production this difference vanishes if injection is into the top of the reservoir (Model 8b). If reinjection is into the middle of the reservoir, the beneficial effect of the high rate of reinjection decreases for the fractured type of reservoir (Model 8a).

![Graph showing steam production rates over time for different models and injection rates](image-url)

a) injection into middle reservoir layer (Model 6a and Model 8a)
b) injection into top reservoir layer (Model 6b and Model 8b)

Figure 2-38  Steam production rates for the homogenous permeability model (Model 6 - lines) and the model with feed zones with an intermediate permeability difference (Model 8 - symbols).

The significance of these results is limited because fractured systems containing two-phase fluid may behave quite different from porous medium systems even in the cases where the fracture spacing is small in comparison to the characteristic dimensions of the problem (Pruess, K., and Narasimhan, T.N., (1982)). The double porosity model that will be discussed in the following chapters of this thesis can be used to represent fractured systems more realistically.

2.4 Summary and conclusions

For the closed system investigated by Sigurdsson et al. (1995), increasing the reinjection rate increases the steam flow. For this study we investigated the effect of reinjection if the system is “opened” by allowing recharge from the top, the sides or the base. Results of our modelling experiments are summarised below.
Lateral recharge:

i) If there is hot recharge from the boundary blocks, steam production from the field is significantly higher than that for laterally closed system. Since reinjection prevents hot natural recharge induced by the pressure drop, and since cold reinjection fluid will cause a decrease in the reservoir temperature, reinjection causes a drop in steam production.

ii) If recharge from the side boundaries is warm, there is no significant difference in steam production, whether there is lateral recharge or not. Reinjection into these systems increases reservoir pressure and prevents the warm water recharge to the production zones. Therefore reinjection is beneficial for increasing steam production. However a high rate of cold reinjection may cause a temperature drop at the production zones.

iii) If the reservoir has strong lateral recharge of warm water from the side boundaries then the sweep of heat from outer zones to the reservoir is efficient. In this case reinjection decreases the temperature of the production zone both by blocking recharge and by the thermal breakthrough of reinjection fluid. Thus reinjection does not significantly increase the steam output. This shows that implementing a closed boundary condition on a large recharge zone around the reservoir will give an over-estimate of the effect of reinjection.

Groundwater recharge:

If the cap-rock is permeable a pressure decline in the reservoir causes recharge of cold groundwater, which results in a considerable decrease in steam flow. Reinjection protects the system from this effect and maintains a long-term high rate of steam production.
Deep recharge:

When the basement rock is sufficiently permeable a pressure decline in the reservoir causes deep recharge which in turn results in an increase in steam flow. Injection may not help in this case since it suppresses deep recharge and thus decreases steam flow.

According to the models discussed in this chapter, the effect of injection into a two-phase liquid dominated geothermal reservoir depends on the recharge conditions. Injection may increase steam flow if recharge is very small and the reservoir is acting as a closed system. It may be beneficial for systems that have a permeable cap-rock because of preventing cold groundwater recharge. But otherwise injection may decrease steam flow from production wells by suppressing hot recharge from depth or replacing lateral recharge by colder injected water.
Chapter 3. Generic Hot-water Systems

3.1 Introduction

In hot-water systems no boiling occurs before or after production commences. Thus large pressure gradients must be set up to cause fluid to flow towards the production wells. Without any injection, however, the pressure will continue to decline until the induced recharge from above, below and laterally matches the overall production rate. In many cases the pressure will drop too low to allow the production wells to continue operation.

Injection assists by providing extra mass and by boosting pressures. From this perspective, it is desirable to have infield injection with injection wells close to production wells in such systems. However, there is a fundamental tension between this beneficial pressure maintenance effect and thermal breakthrough (when the cool injected water reaches the production wells). In some fields, particularly those with a few large faults, thermal breakthrough occurs rapidly and injection wells need to be moved further out e.g. Brady (Krieger and Sponsler (2002)). According to our review of worldwide reinjection experience (Kaya et al. (2009)), whose summary was presented in Chapter 1, thermal breakthrough has been experienced in most hot water reservoirs (Pauzhetsky, Kizildere, East Mesa, Beowawe, Brady, Empire, Steamboat). But infield reinjection has been beneficial in maintaining reservoir pressures in the Pauzhetsky and the Kizildere fields. In some cases moving reinjection wells closer to production wells has had a positive effect by reducing drawdown (Beowawe, Butler et al. (2001)).
It is not desirable to discharge geothermal water to the surface, since it is hot and also contains dissolved materials, principally silica but frequently trace amounts of dangerous heavy metals, such as arsenic and mercury (Horne (1985)). Reinjecting water back into the reservoir is an appropriate solution for disposing of this hot water. However, reinjection can cause ground inflation (e.g. Heber (Stefansson (1997)) and Steamboat Hills (Skalbeck et al. (2002))), groundwater contamination and leakage of reinjected fluid to the surface (Sanyal et al. (1995)). In addition to this, reinjecting into hot-water geothermal systems may be difficult since the amount of hot water to be disposed of is large - greater than that for two-phase liquid-dominated and vapour-dominated geothermal systems. Full or partial surface discharge is still a common practice in many hot water systems worldwide, e.g. at Momotombo, Husavik, Kizildere, Pico Vermelho, Pauzhetsky, Yangbajain, Nagqu, Lihir and Bouillante, (see Kaya et al. (2009)).

A major requirement for an injection well is its intersection of some permeable zones. Other than this requirement, reinjection wells should be cited at an optimum location so that they provide pressure maintenance without causing thermal breakthrough. Determining the type of well configuration that best meets these criteria is the main interest of the research described in this chapter.

To investigate the effect of different well configurations on the production performance of hot water geothermal systems a numerical model of the East Mesa field was chosen as a generic model. The reason for choosing this model to represent hot-water systems are (i) the East Mesa field is a typical hot-water system (Goyal and Kassoy (1978), Riney et al. (1979)) and (ii) there is an existing numerical model of the field at the University of Auckland.

### 3.2 Model Description

#### 3.2.1 Natural state model

In this section a natural state model of the East Mesa field is described. The East Mesa model has a three dimensional, regular, rectangular grid structure. It was set
up to represent the natural state and production behaviour of the field (GeothermEx (1986)). Figure 3-1 shows the areal and vertical grid structure of the 3D East Mesa model. Atmospheric conditions are maintained at the ground surface (1bar and 15°C) while a heat and mass input are applied at the base of the model. The model has 349 columns and 18 layers (6283 blocks including the atmospheric block) extending down to -3035.8m. The locations of the grid-blocks where mass inputs are applied at the basement layer are shown with orange in Figure 3-1. The mass input for the deep inflow varies between 0.01-0.9kg/s and the enthalpy varies between 817.0 and 868.0 kJ/kg.

Figure 3-1  Areal and vertical grid structure of the 3D East Mesa model.

A heat input is applied to all the grid-blocks at the bottom of the model. Figure 3-2 shows the rates of heat input. The heat input is between 2.9-3.07W/m² in the yellow area, 3.41-3.75W/m² in the orange area, 3.83-4.33W/m² in the blue area, 4.41-5.45W/m² in the purple area and 5.62-9.89W/m² in the red area.
Chapter 3. Generic Hot-water Systems

Figure 3-2  Rates for the heat inputs that are applied at the bottom of the model.

The horizontal permeabilities are the same in x and y directions with the highest permeability being 250.0E-15m². The permeability distribution in the reservoir is shown on two vertical cross-sections in Figure 3-3. The locations of the vertical cross-sections are shown in Figure 3-1 by the A-A' and B-B' lines. The black boundaries in Figure 3-3 show the location of the upper and lower production zones. Vertical permeabilities are generally much lower than horizontal permeabilities, with the highest vertical permeability being 3.0E-15m².
Figure 3-3  Horizontal permeability distribution (kx=ky) in the reservoir for: (a) cross-section A-A' and (b) cross-section B-B'.

The mass flows through the system at natural state conditions are shown on the vertical cross-sections in Figure 3-4.
Chapter 3. Generic Hot-water Systems

Figure 3-4 Mass flows in the system for the natural state for: (a) cross-section A-A' and (b) cross-section B-B'.

The temperature distributions in the system at natural state conditions are shown on vertical cross-sections in Figure 3-5. The zones bordered by black lines in this figure are the shallow and deep production zones.
Figure 3-5  Temperature distributions in the system for the natural state for: (a) cross-section A-A’ and (b) cross-section B-B’.
Chapter 3. Generic Hot-water Systems

3.2.2 Production Model

In this section first a production model of the East Mesa field is described and then the modifications that are applied to the production scheme for the model in order to set up a “generic hot-water production model” are explained. The reason for these modifications is to obtain a simple production scheme that allows easy comparison of the results from numerical experiments.

To be able to show the model details clearly, the outer blocks of the East Mesa model are not shown in the following figures. The red squares in Figure 3-6 shows the locations of production wells in the East Mesa field. Several layers are used for production, varying between the ee (-627.9m) and qq (-2304.3m) layers. Hence in the model production is taken from a total of 252 grid-blocks with each grid-block having a different production history.

![Figure 3-6](image)

Figure 3-6 Locations of the production wells and the main production areas in the East Mesa model

In order to simplify the complex production data for the East Mesa field, the production region was divided into four main production areas. The rectangular
areas in Figure 3-6 that are shown as orange, purple, blue and grey are called production areas A, B, C and D, respectively. The production rates from each area, based on the historical data, are shown in Figure 3-7.

![Figure 3-7 Total mass production history for each production area in the East Mesa field.](image)

The production scheme for the East Mesa model that uses 252 production grid-blocks is complicated and does not allow for an easy analysis of the effect of reinjection on production. Therefore for this study a new production scheme was implemented in the model. The new model with the simplified production schedule is named the "generic hot-water model". The simplified production scheme for the generic hot-water model was decided on by considering the position and depth of the actual production wells at the East Mesa field and amalgamating groups of wells. The areal and vertical locations where most of the production wells are located were assigned as production grid-blocks for the generic hot-water model. As shown in Figure 3-8, two production wells were assigned to each
production area and thus the generic hot-water model has a total of only 8 production wells. The production wells in areas A and D produce only from the deep production zones (mm, nn and oo layers), while in areas B and C production is from both the shallow (ff and gg layers) and deep production zones (mm, nn and oo layers). Hence the generic hot-water model has production assigned to 32 grid-blocks.

Table 3-1 shows the names of the 32 grid-blocks assigned for production in the four production areas, the mass flow from each grid-block and the rock properties of the blocks. As can be seen from this table, the deep production zones (mm, nn, oo layers between -1146 and -1878m) have a lower average permeability \(15.75 \times 10^{-15} \text{m}^2\) than the shallow production zones (ff and gg layers between -658m and -780m) where the average permeability is \(78.0 \times 10^{-15} \text{m}^2\). Similarly the deep production zones have lower porosity (10-13%) than the shallow production zones (20-22%).
When the total mass flow (shown in Figure 3-7) for each production area was implemented into the generic hot-water model, there was an excessive pressure decline in all of the production zones and therefore it was not possible to simulate long term production. The reason for the excessive pressure decline in the generic hot-water model is that the reservoir has low vertical permeability and also that there is insufficient recharge from the lateral boundaries. For the generic hot-water
model the total production (shown in Figure 3-7) is taken from 32 grid-blocks, while it is distributed over 252 grid-blocks in the East Mesa Model (Figure 3-6). Additionally in the East Mesa model reinjection is carried out from the beginning of production. Therefore the pressure drawdown in the reservoir was not very high in the East Mesa Model, and the reservoir had enough capacity to produce the required amount of fluid. Since the amount of fluid recharge to the production zones is limited in the generic hot-water model, because of the low vertical permeability and lateral recharge conditions, excessive pressure decline is inevitable.

In later sections of this chapter (Section 3.4), an open lateral boundary for the East Mesa model is considered. It allows recharge from sides of the model in response to production. But first because it is not possible to simulate long term production and injection for the generic hot-water model, with the high amount of production shown in Figure 3-7, we decided to allow a reduction in the amount of mass produced from the system. Instead of implementing the actual mass production history of East Mesa field a deliverability option was used to represent the mass flow from the production wells.

For all production wells the DELT option (autough2 (2008)) was used. It allows discharge proportional to the pressure above some cut-off pressure, with also a limit imposed on the maximum total (steam+liquid) flow. The deliverability equation for the production wells has the form:

\[ q_m = PI \frac{k}{\nu_f} (p - p_{cut-off}) \]  

(3-1)

Here \( q_m \) is the mass flow, \( PI \) is the productivity index, \( k \) is the absolute permeability, \( \nu_f \) is the kinematic viscosity of the fluid, \( p \) is the reservoir pressure and \( p_{cut-off} \) is the trigger pressure at which the well stops flowing.

To decide on a reasonable cut-off pressure a wellbore simulator WELL (Gunn and Freeston (1991)) was run. The pressure loss from the wellhead was calculated as about 63bar, using the depth of the shallowest production block (ff layer -688m),
the given mass flow rate and the natural state temperature and pressure at the production zone. According to Sonnelitter et al. (2000) production pumps are set at depths of -366m to -426m. According to the wellbore simulation, if the cut-off pressure is set at 10 bar at the ff layer (-688m), then the pressure will be 0.53 bar at an average pump depth of 397m. This is the lower limit for which it is possible to continue to the production. Therefore production runs were carried out using the cut-off pressure of 10 bar at the ff layer. The choice of the other deliverability parameters (cut of pressures for deeper production zones, productivity index and maximum steam flow) is explained later in this section. In the production simulations, even for the no-reinjection case, the pressure at the production blocks does not drop down to the cut-off pressure values. For example the cut-off pressure is 10 bar at the ff layer but the minimum pressure reached at the production blocks of this layer is 36.4 bar (see Figure 3-9). This shows that using a cut-off pressure at any value less than 36.4 bar at the ff layer will not change the results of our simulations.

![Figure 3-9](image.png)

**Figure 3-9** Pressure drop at the production grid-blocks at the ff layer for the generic hot-water model for the no-injection case.
Since the assigned cut-off pressure values should be consistent with the vertical location of the production blocks, the cut-off pressures for the production wells were calculated by using the natural state pressure profile of the reservoir. The pressure gradient of the natural state is 1/10.58 bar/m down through the reservoir. The cut-off pressure value for the ff layer (-689m) was set at 10bar and then, using the natural state pressure gradient of 1/10.58 bar/m, the pressures at the lower layers were calculated as 15.8bar, 64.76bar, 87.8bar and 110.9bar for gg(-750m), mm(-1268m), nn(-1512m) and oo(-1756m) layers, respectively (see Figure 3-10 and Table 3-2).

![Figure 3-10 Cut-off pressures for the various production layers.](image)

Table 3-2 shows the deliverability parameters for the production wells used with the DELT option. As shown in the table the productivity index of all the production wells was taken to be 1.60E-12 m³. For this deliverability option we decided to assign a maximum total flow value that limits production at early times when the reservoir pressures are high. This option prevents the occurrence of a very high initial total flow rate.
To obtain appropriate maximum total flow rates, the average production rates from each area were considered. Dividing the average flow rate for each production area by 4.5 gives a reasonable reservoir performance with a small decrease of mass at early stages of production (red line in Figure 3-11) for production area A. It gave a very early decline of mass flow for area C and no decline in mass flow for areas B and D. To obtain similar mass flow histories for all of the production areas the maximum total mass flow values for areas B, C and D were modified. After some experimentation, the maximum total flow rate values presented in Table 3-2 were selected. As can be seen from this table, the maximum total flows from each production area were taken as 90kg/s, 140 kg/s, 150 kg/s and 96kg/s for the production areas A, B, C and D, respectively. Total average flow in the East Mesa model (2170kg/s) is 4.55 times the total flow with this plan.

Table 3-2 Deliverability parameters for the production wells

<table>
<thead>
<tr>
<th>Productivity Index, m³/s</th>
<th>1.60E-12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut-off pressure values</td>
<td></td>
</tr>
<tr>
<td>Layer</td>
<td>ff</td>
</tr>
<tr>
<td>Cut-off pressure, bar</td>
<td>10.00</td>
</tr>
<tr>
<td>Maximum total flow (MTF) values</td>
<td></td>
</tr>
<tr>
<td>Production Area</td>
<td>A</td>
</tr>
<tr>
<td>Number of production grid</td>
<td>6</td>
</tr>
<tr>
<td>MTF from each grid, kg/s</td>
<td>15</td>
</tr>
<tr>
<td>MTF from each production area, kg/s</td>
<td>90</td>
</tr>
</tbody>
</table>

The mass flow histories obtained by using the DELT option, with the parameters given in Table 3-2, are shown in Figure 3-11.
Figure 3-11  Mass production rates for each production area for the generic hot-water model for the no-injection case.

The mass flows through the system after 50 years of production for the no-injection case are shown on the vertical cross-sections in Figure 3-12. A comparison of these flows with the natural state conditions (Figure 3-4) shows that during production, a considerable amount of groundwater recharge occurs into the reservoir from the top of the system. Because the amount of flow is large for production case, a larger scale of flow arrow (8kg/s) is used in Figure 3-12. The scale is 2kg/s for the natural state flows shown in Figure 3-4.
Figure 3-12 Mass flows in the system for the no-injection case after 50 years of production for: (a) cross-section A-A' and (b) cross-section B-B'.

The temperature distributions in the system after 50 years of production for the no-injection case are shown on vertical cross-sections in Figure 3-13(b). A comparison of this figure with Figure 3-5(b) shows that temperatures in the production zones are lower for the production case. The main effect is from the
cold groundwater recharge from the top of the system cooling the production zones.

Figure 3-13 Temperature distributions in the system after 50 years of production for the no-injection case for: (a) cross-section A-A’ and (b) cross-section B-B’.
3.3 Injection Scenarios

3.3.1 Introduction

The main difference between two-phase systems (e.g. Wairakei, Miravalles) and hot-water systems like East Mesa is that no boiling occurs in hot-water geothermal systems before or after production begins. Since no boiling takes place in hot-water systems, after production starts, the reservoir pressure is not buffered by the phase change (boiling). Therefore the failure mechanism in hot-water geothermal fields is pressure decline, to the point where wells can no longer produce. The benefit of reinjection into the reservoir is the maintenance of reservoir pressure, which should reduce the effects of the loss of deliverability.

An optimal reinjection strategy for the hot-water systems should allow the reinjection fluid to support the reservoir pressure while preventing the loss of production performance due to the thermal breakthrough of reinjected water. The distance between production and injection wells determines the benefits of reinjection. Other than the choice of lateral position, reinjection wells can be drilled to intersect formations at shallower, equal or greater depths than the producing formation. How the depth of injection zone effects the production is thus an important matter to consider while deciding on an optimum reinjection strategy for a geothermal field.

In this section various reinjection scenarios were examined to investigate how hot-water geothermal systems can benefit from reinjection and what reinjection pattern gives the best results. The measure of the benefit of reinjection used is the increase in the electrical power output as the consequence of changes in the production enthalpy and reservoir pressure.

Three different reinjection scenarios were tried, varying the horizontal distance between the production and reinjection wells:

1- Close-infield: Within the hot part of reservoir, and each reinjection well is in an adjacent block only 322m away from the closest production well. The reinjection wells are shown with purple in Figure 3-14.
2- Far-infield: Within the hot part of reservoir, but in this case the distance between production blocks and closest far-infield reinjection blocks varies between 640m and 1830m. The reinjection wells are shown with yellow in Figure 3-14.

3- Outfield: Outside the main hot part of reservoir. The distance between production blocks and closest outfield reinjection blocks varies between 939m and 1835m. The reinjection wells are shown with blue in Figure 3-14.

![Figure 3-14 Areal location of the close-infield, far-infield and outfield reinjection blocks](image)

To show the position of the outfield injection wells relative to the hot production zone the temperature distributions at the production layers ff, gg, mm, nn and oo (after 50 years of production without reinjection) are shown in Figure 3-15. The locations of outfield reinjection blocks are shown with black borders (see Section 3.3).
Figure 3-15  Locations of the outfield injection wells superimposed on the temperature distribution at the production layers ff, gg, mm, nn and oo (after 50 years of production without reinjection).

3.3.2 Reinjection experience at East Mesa

In the following sections of this chapter, the results from different reinjection scenarios for the generic hot-water model are compared with the no reinjection case. As this model is based on the East Mesa model first the reinjection experience for East Mesa is reviewed.

The areal locations of the injection wells in the East Mesa model are shown with blue shading in Figure 3-16.
Figure 3-16  Locations of injection wells in the East Mesa model.

The injection capacity of the reinjection zones depends on their permeability. Therefore higher permeability regions need to be used for reinjection. Because reinjection has been carried out successfully at the existing reinjection wells in the East Mesa field, most of the reinjection zones used for this study (Figure 3-14) were chosen from among these locations. Comparison of the reinjection locations used in the present study (Figure 3-14) with the existing reinjection locations at East Mesa (Figure 3-16) shows that not all of the reinjection locations that are used in this study correspond to existing injection wells. The reason for this is that we wish to distribute reinjection reasonably uniformly around production.

In the East Mesa model the vertical locations of the injection blocks are spread across a large interval between the cc (-475m) and qq (-2304m) layers. However the injection wells are mainly located in the gg, hh, ii layers (between -719m and -902m) and in the mm, nn layers (-1146 and -1634).

The injection enthalpy varies between 132.6kJ/kg (31.5°C) and 430.4kJ/kg (103°C) in the East Mesa model. The mass flow weighted average enthalpy of the injection fluid is 334.9kJ/kg.
3.3.3 Reinjection scenarios

Each of the main scenarios discussed in Section 3.3.1 has three sub-cases of reinjection into shallow, intermediate and deep levels. Table 3-3 shows the reinjection scenarios and the different reinjection depths. The shallow and intermediate zones correspond to the main injection depths used at East Mesa whereas there are few wells in our deep zone.

**Table 3-3 Reinjection Scenarios and different cases of reinjection depth**

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Cases</th>
<th>Reinjection depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1- Close-infield</td>
<td>a- Shallow</td>
<td>between -658m and -780m</td>
</tr>
<tr>
<td>(322m away)</td>
<td>b- intermediate</td>
<td>between -1146m and -1634m</td>
</tr>
<tr>
<td></td>
<td>c- Deep</td>
<td>between -1878m and -2121m</td>
</tr>
<tr>
<td>2- Far-infield</td>
<td>a- Shallow</td>
<td>between -658m and -780m</td>
</tr>
<tr>
<td>(640m - 1830m away)</td>
<td>b- intermediate</td>
<td>between -1146m and -1634m</td>
</tr>
<tr>
<td></td>
<td>c- Deep</td>
<td>between -1878m and -2121m</td>
</tr>
<tr>
<td>3- Outfield</td>
<td>a- Shallow</td>
<td>between -658m and -780m</td>
</tr>
<tr>
<td>(939m - 1835m away)</td>
<td>b- intermediate</td>
<td>between -1146m and -1634m</td>
</tr>
<tr>
<td></td>
<td>c- Deep</td>
<td>between -1878m and -2121m</td>
</tr>
</tbody>
</table>

The PINJ option that allows a fraction of the production of a group of wells to be injected into another well (autough2 (2008)) was used to represent reinjection into reservoir. This option allows the total amount of reinjection fluid to be distributed equally between the reinjection grid-blocks. This give the target maximum flow for each injection well and then the actual flow is controlled by the reservoir pressures and the injectivity parameters given in Table 3-4.

In the East Mesa model, the average enthalpy of the injection fluid is 334.9kJ/kg. Therefore for the present model the enthalpy of reinjection fluid was taken as 334.9kJ/kg (80°C) for all reinjection wells. The injectivity index for all reinjection wells was set to be the same as the productivity index at 1.60E-12 m³.

Table 3-4 summarizes the reinjection parameters used for all reinjection scenarios.
### Table 3-4 Reinjection parameters

<table>
<thead>
<tr>
<th>Reinjection fraction</th>
<th>total produced liquid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productivity index of injection wells, m³</td>
<td>1.60E-12</td>
</tr>
<tr>
<td>Reinjection enthalpy, kJ/kg</td>
<td>334.9</td>
</tr>
<tr>
<td>Reinjection temperature, °C</td>
<td>80</td>
</tr>
</tbody>
</table>

### 3.4 Close-infield reinjection scenario

#### 3.4.1 Scenario description

The literature survey of reinjection experiences (Chapter 1) shows that infield reinjection is a common strategy in geothermal fields. In most cases existing production or investigation wells, usually located in the middle of the field, are used first for reinjection. This strategy is normally adopted to reduce costs during the early stages of field development. The location of infield reinjection wells can be close to the production wells or they can be relatively far away.

In this part of the study we investigate the effect of close-infield reinjection on the production enthalpy and mass flows, and on the reservoir pressure and electrical power output of the field. The areal location of the production and reinjection wells is shown by red and blue shadings, respectively in Figure 3-17. The areas bordered with orange, purple, yellow and grey show the A, B, C and D production areas, respectively. The vertical locations of these production blocks are also shown in Figure 3-17(b). Since production and reinjection wells are located at the centres of the grid-blocks, the horizontal distance between a production well and the closest reinjection well is 322m.
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Figure 3-17 Locations of production wells (red) and reinjection wells (blue) for the close-infield reinjection scenario.

As is shown in Table 3-3 three zones for reinjection were tried in order to investigate the effect of reinjection depth on the production capacity of the reservoir. The vertical locations of the reinjection blocks are shown in Figure 3-17(b) for the three cases of shallow, intermediate and deep reinjection. As can be seen from this figure the shallow reinjection zone is the ff and gg layers (between -658m and -780m) while the intermediate reinjection zone is the mm and nn layers (between -1146m and -1634m) and the deep reinjection zone is the pp layer (between -1878m and -2121m).

The reservoir pressure histories of representative grid-blocks (the grid-blocks that are located in the middle of each production area and at the intermediate production layer nn) are plotted in various figures below.

Table 3-5 gives the representative grid-blocks for each production area.
Table 3-5  Representative grid-blocks used to plot the reservoir pressures for each production area

<table>
<thead>
<tr>
<th>Production Area</th>
<th>Grid-block</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>nn184</td>
</tr>
<tr>
<td>B</td>
<td>nn134</td>
</tr>
<tr>
<td>C</td>
<td>nn 84</td>
</tr>
<tr>
<td>D</td>
<td>nn 34</td>
</tr>
</tbody>
</table>

3.4.2 Case1(a): Close-infield reinjection into shallow zones

In this case close-infield reinjection was applied into the shallow zone.

Figure 3-18 compares reservoir pressure histories for each production area for the no-injection case and reinjection Case1(a). In all production areas, pressures are much higher with reinjection (Case1(a)).

Figure 3-18  Reservoir pressures in the production areas A, B, C and D for the no-injection case and reinjection Case1(a).
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For Case 1(a) mass production does not decrease from the maximum total value assigned as one of the deliverability parameter. The value of constant mass production from each production area for 50 years is as shown in Table 3-6.

Table 3-6 Total mass flow rates from each production area for Case 1(a)

<table>
<thead>
<tr>
<th>Production Area</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass flow from each production area, kg/s</td>
<td>90</td>
<td>140</td>
<td>150</td>
<td>96</td>
</tr>
</tbody>
</table>

The effect of shallow reinjection on production was investigated by plotting production enthalpy over the 50 years production time for each production area (see Figure 3-19). Reinjection into the shallow zone produces a significantly lower enthalpy than the no-reinjection case for production areas B and C which produce from both the shallow and deep zones. The reason for this enthalpy drop is that the reinjected water arrives at the shallow production zone within a very short time, and affects the temperature of the production fluid. Because of the low vertical permeability, the deep production zones are not affected by premature breakthrough of reinjection water. Hence in the production areas A and D that produce only from the deep zone, the production enthalpies are higher for the shallow reinjection case (Case 1(a)) than the case of no-reinjection.
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Figure 3-19 Production enthalpies for the production areas A, B, C and D for the no-injection case and reinjection Case1(a).

The higher production enthalpy with injection for production areas A and D is due to the effects of the support of the reservoir pressure by injection. The mass flows in the system for Case1(a) are shown in Figure 3-20. Comparing this figure with Figure 3-12 shows that while there is a strong groundwater recharge to the reservoir for the no-injection case, it disappears for the shallow reinjection case. Since there is no cold groundwater recharge, the enthalpy of the production areas A and D stays higher.

Figure 3-21 shows the temperature distributions in the system for Case1(a). Comparison of this figure with Figure 3-13 shows that shallow production zones are significantly colder for the shallow reinjection case (Case1(a)) than those for the no-reinjection case.
Figure 3-20  Mass flows in the system for Case 1(a) after 50 years of production: (a) cross-section A-A’ and (b) cross-section B-B’.
Figure 3-21 Temperature distributions in the system after 50 years of production for Case 1(a) for: (a) cross-section A-A' and (b) cross-section B-B'.
3.4.3 Case1(b): Close-infield reinjection into intermediate depth zones

This section discusses the case of close-infield reinjection (Figure 3-17(a)) into intermediate depth zones (see Figure 3-17(b)). Figure 3-22 shows reservoir pressure histories for Case1(b) and the no-reinjection case. According to this figure, close-infield reinjection into the intermediate zones results in a slight increase in the reservoir pressures over the 50 years of production for all the production areas.

![Reservoir pressures in the production areas A, B, C and D for the no-injection case and reinjection Case1(b).](image)

As for Case1(a), the mass production does not decrease throughout the 50 years of production. The constant mass production from each production area for 50 years is as shown in Table 3-6.
The effect of intermediate depth reinjection on the production enthalpy is shown in Figure 3-23. According to this figure, close-infield, intermediate depth reinjection does not affect the production enthalpy for about the first 5 years of production. However after 5 years the reinjection wells cause interference with the production wells, and significant thermal breakthrough occurs in all production areas. The production enthalpy starts to drop almost linearly.

![Figure 3-23 Production enthalpies for the production areas A, B, C and D for the no-injection case and reinjection Case1(b).](image)

The mass flows in the system after 50 years of production for Case1(b) are shown in Figure 3-24 for two vertical cross-sections. According to this figure there is no strong groundwater recharge to the system. The reason for this is that the reinjection fluid supports the reservoir pressure and prevents groundwater recharge, the same as for Case1(a).
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Figure 3-24  Mass flows in the system after 50 years of production for Case1(b) for: (a) cross-section A-A' and (b) cross-section B-B'.

The temperature distributions in the system after 50 years of production for Case1(b) are shown on vertical cross-sections in Figure 3-25. Comparison of this figure with Figure 3-13 shows that the temperatures at the deep production layers are lower for Case1(b) than those for the no-reinjection case.
Figure 3-25 Temperature distributions in the system after 50 years of production for Case1(b) for: (a) cross-section A-A’ and (b) cross-section B-B’.
### 3.4.4 Case1(c): Close-infield reinjection into deep zones

Next close-infield reinjection (see Figure 3-17(a)) was applied into the deep zone (Figure 3-17(b)).

The effect of this strategy on reservoir pressures is shown in Figure 3-26. According to this figure although deep reinjection does not increase reservoir pressure as much as intermediate reinjection (see Figure 3-22), it still maintains reservoir pressure strongly in all production areas.

![Figure 3-26 Reservoir pressures in the production areas A, B, C and D for the no-injection case and reinjection Case1(c).](image-url)

Mass production does not decrease throughout the 50 years of production. The production rate from each area for 50 years is as shown in Table 3-6.

To determine the effect of deep reinjection on production, the production enthalpy was plotted for each production area (Figure 3-27). The mass flows in the system...
after 50 years of production are shown in Figure 3-28 for the A-A' and B-B' cross-sections.

![Graphs showing production enthalpies for different cases](image)

Figure 3-27 Production enthalpies for the production areas A, B, C and D for the no-injection case and reinjection Case1(c).

According to Figure 3-26, deep reinjection helps to maintain pressure in reservoir and Figure 3-27 shows that this prevents cold water recharge and hence the production enthalpies are higher than for the no-reinjection case. However for production areas A and D where production is only from the deep layers a higher enthalpy drop is observed, indicating that these areas are affected more by the breakthrough of reinjected cold water. This is to be expected because of the close proximity of the production and reinjection wells. A comparison of Figure 3-28 with Figure 3-12 shows that deep reinjection increases the upflow from the reinjection zones to the reservoir. A comparison of Figure 3-29 and Figure 3-13
shows the breakthrough effect, with the temperatures at the deep production zones being lower for the Case1(c) than for the no-reinjection case.

Figure 3-28  Mass flows in the system after 50 years of production for Case1(c) for: (a) cross-section A-A' and (b) cross-section B-B'.
3.4.5 Power output for the close-infield reinjection case

Electricity output of hot-water geothermal systems depends on power plant configuration. However from practical experience the power plant efficiency is
generally close 10% and following equation can be used to calculate power output (Zarrouk (2009)).

\[ Q = m \cdot h \times 10\% \]  

(3-2)

Here Q is the electricity output, kW, m is mass flow, kg/s, and h is production enthalpy kJ/kg.

Figure 3-30 shows a comparison of the power output for the no-injection case and the three cases of close-infield reinjection.

During the first 15 years shallow close-infield reinjection (Case1(a)) causes detrimental effects on power production. But for all cases reinjection results in a higher power output than for the no-reinjection case in the long term. The deep close-infield reinjection scenario (Case1(c)) produces the highest power output.

Figure 3-30 Power output for the no-injection scenario and injection scenarios Case1(a), Case1(b) and Case1(c).
3.5 Far-infield reinjection scenario

3.5.1 Scenario description

In this section the effect of far-infield reinjection on the production enthalpy of the production fluid and electricity output of the field are investigated. According to the worldwide reinjection experience presented in Chapter 1 this strategy is often applied in hot-water reservoirs if thermal breakthrough from close-infield reinjection is observed in the production wells e.g. East Mesa, Brady.

For this scenario reinjection wells are located inside the production area, however the distance between production well and closest reinjection well is quite large, varying between about 640m and 1830m. The areal locations of the production and reinjection wells are shown with red and blue, respectively, in Figure 3-31(a). This figure also shows the vertical locations of each production area. As for the close-infield reinjection scenario, three depths of reinjection were tried to investigate the effect of reinjection depth on the production capacity of the reservoir. The vertical locations of the reinjection blocks are shown in Figure 3-31(b) for these three cases.

![Figure 3-31 Locations of production (red) and reinjection (blue) wells for the far-infield reinjection scenario.](image)
3.5.2 Case2(a): Far-infield reinjection into shallow zones

Far-infield reinjection was applied into shallow zones between -658m and -780m (see Figure 3-31(b)). The reservoir pressures histories for each production area for the no-injection case and reinjection Case2(a) are compared in Figure 3-32. The close-infield reinjection case, Case1(a) is also plotted in this figure. This figure shows that there is no difference in the reservoir pressure histories between the close-infield and far-infield scenarios, and in both cases the pressure does not drop as much as for the no-reinjection case.

![Figure 3-32 Reservoir pressures in the production areas A, B, C and D for the no-injection case (red), reinjection Case1(a)(dark blue) and Case2(a)(light blue).](image)

The mass production stays constant at the maximum total value assigned as one of the deliverability parameters. The mass production from each production area for the 50 years is as shown in Table 3-6.
The production enthalpy histories for the three cases are presented together in Figure 3-33. In this figure the production enthalpy histories for shallow close-infield reinjection (Case1(a)), shallow far-infield reinjection (Case2(a)) and no-injection are represented by dark blue, light blue and red, respectively. For production areas B and C, no significant enthalpy drop occurs compared to the no-injection case. Moving the reinjection wells to the far-infield zones reduces the thermal breakthrough effect seen in the shallow production zones for Case1(a).

![Figure 3-33](image)

**Figure 3-33** Production enthalpies for the production areas A, B, C and D for the no-injection case (red), Case1(a) (dark blue) and Case2(a) (light blue).

For production areas A and D, the far-infield reinjection scenario gives similar enthalpies to those for the close-infield scenario. Because there is no shallow production from these areas, they are not affected by thermal breakthrough of shallow reinjection for either Case1(a) or Case2(a).
The mass flows for this case are shown in Figure 3-34. Reinjection fluid in the far-infield zones mainly moves laterally through the reservoir because of the low vertical permeability giving preference to the recharge from large boundary blocks. Figure 3-35 shows temperature distributions in the system for Case2(a). Comparing this figure with Figure 3-21 shows that reinjecting far-infield does not cause as much temperature decline in the shallow production zone as for the close-infield case.

![Figure 3-34](image)

Figure 3-34 Mass flows in the system after 50 years of production for Case2(a) for: (a) cross-section A-A’ and (b) cross-section B-B’.
Figure 3-35  Temperature distributions in the system after 50 years of production for Case2(a) for: (a) cross-section A-A’ and (b) cross-section B-B’.
3.5.3 Case2(b) – Far-infield reinjection into intermediate zones

As in Case1(b) reinjection is located in the layers between -1146m and -1634m but now at a longer distance from the production wells (see Figure 3-31).

Figure 3-22 shows reservoir pressure histories for Case1(b), Case2(b) and the no-reinjection case. Far-infield reinjection into intermediate zones prevents a pressure drop in the reservoir for all production areas. But far-infield reinjection does not support the reservoir pressure as much as close-infield reinjection.

Figure 3-36 Reservoir pressures in the production areas A, B, C and D for the no-injection case (red) and reinjection Case1(b) (dark blue) and Case2(b) (light blue).

For this case, the mass production does not decrease throughout the 50 years of production. The amount of mass production from each production area for 50 years is as shown in Table 3-6.
Figure 3-37 shows production enthalpies for the no-reinjection case (red), Case1(b) (dark blue) and Case2(b) (light blue). According to this figure moving the reinjection wells from close-infield to far-infield significantly improves the enthalpy of the production fluid. Since in this case the production zones are mainly located at the same level as the reinjection layers, moving the reinjection wells away from the production zones eliminates breakthrough and prevents the decline of enthalpies.

As can be seen from the comparison of the flows shown in Figure 3-38 with those in Figure 3-12 reinjecting into intermediate layers prevents cold groundwater recharge. This explains why the production enthalpies for Case2(b) are higher than for the no-reinjection case.
Figure 3-38 Mass flows in the system after 50 years of production for Case2(b) for: (a) cross-section A-A' and (b) cross-section B-B'.

Comparison of the temperature distributions in Figure 3-39 and Figure 3-25 shows that injecting into intermediate levels for the far-infield case (Case2(b)) does not decrease the temperature of the deep production zones as much as in the close-infield reinjection case (Case1(b)).
Figure 3-39  Temperature distributions in the system after 50 years of production for Case2(b) for: (a) cross-section A-A’ and (b) cross-section B-B’.
3.5.4 Case 2(c): Far-infield reinjection into deep zones

In this case far-infield reinjection (see Figure 3-17) was applied into the deep zone (layers between -1878m -2121m). The effect of reinjection on reservoir pressures is shown in Figure 3-40. This figure shows that reservoir pressure is strongly supported in all production areas by deep reinjection. There is no significant difference in terms of pressure maintenance between the far-infield and close-infield scenarios.

![Figure 3-40 Reservoir pressures in the production areas A, B, C and D for the no-injection case (red) and reinjection Case 1(c) (dark blue), Case 2(c) (light blue).](image)

Mass production does not change throughout the 50 years of production. The mass production from each production area for 50 years is as shown in Table 3-6.

The effect of deep reinjection on the production enthalpy is shown in Figure 3-41. For the deep reinjection case, moving the reinjection wells away from production...
wells considerably improves the production enthalpy in all production areas. Production enthalpies for areas A and C slightly increase in early times (first 8 years), because injection water displaces the hot water from deep zones to the production zones. Similar behaviour is observed in the case of close infield reinjection into deep zones (Case 1 (c)) for area C (Figure 3-41).

Figure 3-41 Production enthalpies for the production areas A, B, C and D for no-injection, Case1(c) (dark blue) and Case2(c) (light blue).

Reinjection fluid applied near the bottom of the reservoir flows horizontally and vertically (see Figure 3-42). Because there is no apparent groundwater recharge or thermal breakthrough effect (see Figure 3-43), the production enthalpy does not decrease very much.
Figure 3-42  Mass flows in the system after 50 years of production for Case2(c) for: (a) cross-section A-A' and (b) cross-section B-B'.
Figure 3-43 Temperature distributions in the system after 50 years of production for Case 2(c) for: (a) cross-section A-A' and (b) cross-section B-B'.

3.5.5 Power output for the far-infield reinjection case

Figure 3-44 shows a comparison of power output for the no-injection case and the three cases of far-infield reinjection. According to this figure the far-infield
reinjection increases the power output significantly for any reinjection depth. Thermal breakthrough is most noticeable in the shallow reinjection case, and hence Case2(a) produces less power. According to these results the best option for far-infield reinjection scenario is the deep reinjection case (Case2(c)).

![Figure 3-44 Power output for the no-injection and injection scenarios Case2(a), Case2(b) and Case2(c)](image)

3.6 Outfield reinjection scenario

3.6.1 Scenario description

Outfield reinjection is also an option used in some geothermal fields. According to the review of worldwide reinjection experience given in Chapter 1, this strategy is generally applied to reduce the risk of cold water returning to the production area. Field experiences show that reinjection wells are generally moved outfield, fully or
partially, when the adverse thermal breakthrough effects of infield reinjection are observed.

For this scenario reinjection wells were located further away from the production wells and outside the hot part of system. The distance between a production well and the closest reinjection well varies between 939m and 1835m. The areal locations of production and reinjection wells are shown with red and blue shading, respectively, in Figure 3-45(a). Three reinjection depths were used with this scenario as well. The vertical locations of reinjection blocks for each case are shown in Figure 3-45(b).

Figure 3-45 Locations of the production (red) and reinjection (blue) wells for the outfield reinjection scenarios.

3.6.2 Case3(a): Outfield reinjection into shallow zones

Reinjection was made into the outfield shallow zones between -658m and -780m depth (Figure 3-45(b)).
The reservoir pressure histories for each production area for the no-injection case and reinjection Case2(a) and Case3(a) are compared in Figure 3-46. For the case of outfield reinjection into shallow layers, the reservoir pressure does not drop as much as for the no-reinjection case. In fact Case3(a) shows higher pressures than the no-reinjection case for all of the production areas. Similar pressure histories are observed when reinjection is carried out into the far-infield (Case2(a)).

![Figure 3-46 Reservoir pressures in the production areas A, B, C and D for the no-injection case (red), and for far-infield reinjection Case2(a) (light blue) and out-field reinjection Case3(a) (dark blue).](image)

The mass production does not change throughout the 50 years of production. The mass production rates from each production area for 50 years are as shown in Table 3-6.

In Figure 3-47 the production enthalpy histories are presented for scenarios with shallow outfield reinjection (Case3(a)), shallow far-infield reinjection (Case2(a)) and no-reinjection. According to this figure for the production areas A and D,
which have no production from shallow zones, the effect of shallow reinjection on enthalpy is similar whether the injection wells are located far-infield or outfield. For production areas B and C the enthalpies are higher when shallow reinjection is applied into the outfield zones indicating a reduced effect of reinjection returns.

Figure 3-47 Production enthalpies for the production areas A, B, C and D for the no-injection case (red), Case2(a) (light blue) and Case3(a) (dark blue).

The mass flows for this case are shown in Figure 3-48. Reinjection fluid injected into outfield zones moves inside the reservoir and prevents cold groundwater recharge by maintaining the reservoir pressure.
Figure 3-48  Mass flows in the system after 50 years of production for Case3(a) for: (a) cross-section A-A' and (b) cross-section B-B'.

The temperatures at the shallow zones for Case3(a) (Figure 3-49) are higher than those for Case2(a) (Figure 3-35). This indicates that the shallow production zone is not affected as much by an early return of reinjection fluid for the case of outfield reinjection as for the case of far-infield reinjection.
Figure 3-49  Temperature distributions in the system after 50 years of production for Case3(a) for: (a) cross-section A-A' and (b) cross-section B-B'.
3.6.3 Case3(b) – Outfield reinjection into intermediate zones

In this case reinjection is made into the intermediate depth layers between -1146m and -1634m from outfield wells (see Figure 3-45).

The effect of outfield, intermediate zone reinjection on reservoir pressures is shown in Figure 3-50. According to this figure, reinjection into outfield intermediate depth zones prevents a high pressure drop and keeps the reservoir pressure high throughout the 50 years of production. Because of the longer distance, and hence smaller communication between the production and reinjection wells, outfield reinjection does not support the reservoir pressure as much as far-infield reinjection.

Figure 3-50  Reservoir pressures in the production areas A, B, C and D for the no-injection case (red), reinjection Case2(b) (light blue) and Case3(b) (dark blue).
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The mass production does not change throughout the 50 years of production. (see Table 3-6).

Figure 3-51 shows the production enthalpies for the no-reinjection case, Case2(b) (light blue) and Case3(b) (dark blue). According to this figure, for the areas producing only from the deep zones (area A and D), moving reinjection wells from far-infield to outfield decreases the production enthalpies. The reason for this is that the permeability of the outfield reinjection zones is smaller than the far-infield zones, around the deep production area (see Figure 3-3). Hence reinjecting into the system from outfield does not support the pressure of the production area as much as far-infield reinjection (Figure 3-50). Thus it allows inflow of warm recharge to the deep production areas from the surrounding blocks, as can be seen from the comparison of the flows in Figure 3-52 and Figure 3-38. Since in both Case 2(b) and Case 3(b) the production zone is far away from the reinjection zone, the enthalpies of the fluid produced both from shallow and deep zones (in areas B and C) are not affected discernibly by a shift of reinjection out-field.

Figure 3-51  Production enthalpies for the production areas A, B, C and D for the no-injection case (red), Case2(b) (light blue) and Case3(b)(dark blue).
Figure 3-52 Mass flows in the system after 50 years of production for Case 3(b) for: (a) cross-section A-A' and (b) cross-section B-B'.

A comparison of Figure 3-53 and Figure 3-39 shows that, at some of the regions in the deep production zones, reservoir temperatures are colder for the far-infield reinjection case than those for the outfield reinjection case. The cold regions correspond to the location of reinjection wells. However this comparison also shows that for the far-infield reinjection case the temperatures of the regions that are away from reinjection wells are not affected by reinjection. In fact the deeper
parts of the deep production zones have higher temperatures for the far-infield reinjection case. This is because of the cooler lateral recharge from the side blocks for the outfield reinjection case (see Figure 3-52).

Hence the amount of energy that is swept into the production zones by the reinjection fluid for the far-infield case (Case2b) is higher than that for the outfield reinjection case (Case3b). Therefore the production enthalpies are lower for the outfield reinjection case (Case3b).
Figure 3-53  Temperature distributions in the system after 50 years of production for Case3(b) for: (a) cross-section A-A' and (b) cross-section B-B'.

3.6.4 Case3(c): Outfield reinjection into the deep zone

In this case the effect of outfield reinjection into the deep zone was investigated. Reinjection was applied into the layers between -1878m and -2121m (see Figure 3-45(b)).

Figure 3-54 compares the reservoir pressure histories for Case3(c), Case2(c) and the no-reinjection case. The figure shows that although outfield injection does not support the reservoir pressure as much as far-infield reinjection, injection into the deep zones of the outfield reinjection blocks prevents an excessive pressure drop in the reservoir over the 50 years of production.
Figure 3-54 Reservoir pressures in the production areas A, B, C and D for the no-injection case, far-infield deep reinjection Case2(c) and out-field deep reinjection Case3(c).

The mass production does not change throughout the 50 years of production. The mass production from each production area for 50 years is as shown in Table 3-6.

The effect of deep reinjection on the production enthalpy is shown in Figure 3-55. According to this figure moving the reinjection wells from far-infield to outfield decreases the production enthalpies at all production areas. The outfield reinjection wells are located at the bottom and outside of the main production area, and in a low horizontal permeability zone (see Figure 3-3). Therefore the fluid injected from this area does not sweep much heat from deep part of the system into the production zones. Because the far-infield deep zone has a higher permeability than the outfield deep zone, the circulation of injected fluid in the reservoir is easier in this case. This can be seen from a comparison of the flows shown in Figure 3-56 and Figure 3-42. Hence moving the deep injection wells from far-infield to outfield zones decreases the heat sweep through the reservoir to production wells,
and consequently results in a lower production enthalpy from both the upper and lower production zones.

Figure 3-55 Production enthalpies for the production areas A, B, C and D for the no-injection case (red), Case2(c) (light blue) and Case3(c)(dark blue).
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Figure 3-56 Mass flows in the system after 50 years of production for Case3(c) for: (a) cross-section A-A’ and (b) cross-section B-B’.

The temperature distributions in the system after 50 years of production for the deep-outfield reinjection case (Case3(c)) are shown on vertical cross-sections in Figure 3-57. Comparison of this figure with Figure 3-43 shows that for the deep reinjection there is not much difference between the temperatures of the production zones between the far-infield or outfield reinjection cases.
Figure 3-57 Temperature distributions in the system after 50 years of production for Case3(c) for: (a) cross-section A-A’ and (b) cross-section B-B’.

3.6.5 Power output for the outfield reinjection scenario

Figure 3-58 shows a comparison of power output for the no-injection case and three cases of outfield reinjection. According to this figure outfield reinjection has
a strong impact on the power output of the system. Increasing the depth of reinjection increases the power production. Thus for the outfield reinjection scenario the deepest reinjection produces the highest power output.

Figure 3-58  Power output for the no-injection scenario and injection scenarios Case3(a), Case3(b) and Case3(c)

Figure 3-59 summarises the effect of the distance between the production and reinjection wells on power output for each reinjection depth. According to this figure the following comments can be made:

- If reinjection is applied into the shallow zone a longer distance between production and reinjection wells results in a higher power output (Figure 3-59a).

- For intermediate depths, close-infield reinjection (Scenario-1) gives the lowest power output. Increasing the distance between production and injection wells by implementing far-infield reinjection (Scenario-2), significantly increases the power output. However a further increase of
distance between the wells causes a slight decrease of power output. (Figure 3-59b).

- Figure 3-59c shows that for the deep reinjection case, the areal location of the reinjection wells (close-infield, far-infield or outfield) does not affect power output as much as for the shallow or intermediate reinjection cases. As in intermediate reinjection cases (Figure 3-59b), far-infield reinjection produces the highest amount of power, while close-infield produces the lowest.
3.7 Injection Scenarios for the Laterally Open Model

The model used for the scenarios described in Section 3.2 and 3.3 did not allow mass to flow across the sides. This causes a large pressure drawdown in response to production and it is not possible to run the model for a high rate of mass production for the no-reinjection case. In this section a laterally open model is used, with recharge boundary conditions that allow mass to flow across the boundary in response to a pressure increase or decrease.

The generic hot-water model described in Section 3.2.2 is used as the base model and recharge boundary blocks are added. The new model is named the laterally open model. To allow lateral recharge from the side boundary blocks into the system the RECH option is used (see equation (3-3))

\[ q_m = \alpha (p - p_o) \]  \hspace{1cm} (3-3)

Here \( q_m \) is the mass flow entering the block from the lateral boundaries of the model, \( p \) is the current pressure in the block, \( p_o \) is the natural state pressure for the

Figure 3-59 Power output for the no-injection scenario and three different reinjection scenarios for (a) shallow (b) intermediate and (c) deep reinjection depths.
block and $\alpha$ is the recharge coefficient (O’Sullivan (2006)). This option keeps the enthalpy of the recharge fluid the same as the initial enthalpy of the boundary block. Thus if the block is hot initially, then the recharge is hot and if it is cold, the recharge is cold. The range of the value of the recharge coefficients ($\alpha$) are given in the Table (xx) for each layer. They vary with the size of the block and permeability.

Table 3-7 Recharge coefficient ranges for each layer.

<table>
<thead>
<tr>
<th>layer</th>
<th>Min $\alpha$, m$^3$</th>
<th>Max $\alpha$, m$^3$</th>
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<tr>
<td>aa</td>
<td>2.75E-06</td>
<td>2.02E-05</td>
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<tr>
<td>bb</td>
<td>1.79E-06</td>
<td>1.46E-05</td>
</tr>
<tr>
<td>cc</td>
<td>1.38E-06</td>
<td>1.12E-05</td>
</tr>
<tr>
<td>dd</td>
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<td>ii</td>
<td>8.95E-07</td>
<td>9.69E-06</td>
</tr>
</tbody>
</table>

<table>
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<td>4.00E-06</td>
</tr>
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<td>qq</td>
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</tr>
<tr>
<td>rr</td>
<td>8.82E-08</td>
<td>3.92E-06</td>
</tr>
</tbody>
</table>

The same 32 grid-blocks as for the generic hot-water model are used as production wells in the four production areas (see Table 3-1). Again the DELT option is used to represent the deliverability of the production wells. Since a higher rate of production is going to be simulated in this section, to decide on the maximum total flow values for each production area, the production histories for the East Mesa field (see Figure 3-7) were considered. The average mass flow from each production area was calculated and this value was distributed evenly among the production grid-blocks in each production area. The production well parameters used in the laterally open model are shown in Table 3-8.

Table 3-8 Deliverability parameters for the production wells in the laterally open model

<table>
<thead>
<tr>
<th>Productivity Index, m$^3$</th>
<th>1.60E-12</th>
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</thead>
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<tr>
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</tr>
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<td>Layer</td>
<td>ff</td>
</tr>
<tr>
<td>Cut-off pressure, bar</td>
<td>10.00</td>
</tr>
<tr>
<td>Maximum total flow (MTF) values</td>
<td></td>
</tr>
<tr>
<td>Production Area</td>
<td>A</td>
</tr>
</tbody>
</table>
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<table>
<thead>
<tr>
<th>Number of production grid</th>
<th>6</th>
<th>10</th>
<th>10</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTF from each grid, kg/s</td>
<td>67</td>
<td>53</td>
<td>92</td>
<td>52</td>
</tr>
<tr>
<td>MTF from each production area, kg/s</td>
<td>402</td>
<td>530</td>
<td>920</td>
<td>312</td>
</tr>
</tbody>
</table>

The mass flow histories obtained by using the laterally open model with the parameters given in Table 3-8 are shown in Figure 3-60 for the no-injection case.

![Figure 3-60](image)

**Figure 3-60** Mass production rates for each production area for the laterally open model for the no-injection case.

As in Section 3.3, the reservoir pressure histories are plotted for representative grid-blocks. These grid-blocks are located in the middle of each production area and at the intermediate production layer nn. Table 3-5 shows these representative grid-blocks for each production area.

The mass flows in the system after 50 years of production for the no-injection case are shown in Figure 3-61. This figure shows there is a considerable amount of lateral recharge into the reservoir from the side boundaries of the model.
Figure 3-61  Mass flows in the system for the laterally open model, after 50 years of production, for the no-injection case for: (a) cross-section A-A’ and (b) cross-section B-B’.

The temperature distributions in the system after 50 years of production for the no-injection case are shown on vertical cross-sections in Figure 3-62 for the laterally open model. A comparison of this figure with Figure 3-5 shows that temperatures in production zones are lower for the production case than in the natural state. The
main reason for this cooling in the production zones is lateral recharge from the sides of the system.

Figure 3-62  Temperature distributions in the system for the laterally open model, after 50 years of production, for the no-injection case for: (a) cross-section A-A’ and (b) cross-section B-B’.
The PINJ option was used for the reinjection wells, as for the generic hot-water model. The reinjection parameters used for all reinjection scenarios are summarized in Table 3-4.

### 3.8 Outfield reinjection scenario for the laterally open model

#### 3.8.1 Introduction

In this part of the study, the effect of outfield reinjection on the laterally open model is investigated. The areal locations of production and reinjection wells are shown with red and blue shadings, respectively, in Figure 3-45(a). Three cases for the vertical location of the reinjection zone were tried for this scenario. The vertical locations of the reinjection blocks for each case are shown in Figure 3-45(b).

#### 3.8.2 Case4(a): Outfield reinjection into shallow zones for the laterally open model

Reinjection was made into outfield shallow zones of the reservoir between -658m and -780m depth (Figure 3-45(b)).

The mass production histories for each production area for the no-injection case and reinjection Case4(a) are compared in Figure 3-63. This figure shows that, for Case4(a), mass production does not drop as much as for the no-reinjection case. The areas B and C that produces from the shallow zones, show a larger difference between the no-reinjection case and Case4(a). This shows that there is higher amount of cold reinjection fluid entering into these areas in response to production.
Figure 3-63 Mass production rates from the production areas A, B, C and D for the no-injection case and Case4(a).

Reservoir pressure histories for each production area for the no-injection case and reinjection Case4(a) are compared in Figure 3-64. This figure shows that outfield reinjection into the shallow layers of the laterally open model prevents a large pressure drawdown in the reservoir.
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Figure 3-64 Reservoir pressures in the production areas A, B, C and D for the no-injection case and Case4(a).

The effect of deep reinjection on the production enthalpy is shown in Figure 3-65. As can be seen from the comparison of Figure 3-61 and Figure 3-66, cold reinjection into the outfield shallow zones decreases lateral recharge. There is some down-flow of reinjection fluid. Due to the breakthrough of cold reinjection fluid, the production enthalpy decreases for all the production areas. The production areas that produce from both the shallow and deep zones (area B and C) are affected more by thermal breakthrough since the shallow injection zones are close to the shallow production wells.
Figure 3-65  Production enthalpies for the production areas A, B, C and D for the no-injection case and for Case4(a).
Figure 3-66 Mass flows in the system for the laterally open model, after 50 years of production, for Case 4(a) for: (a) cross-section A-A' and (b) cross-section B-B’.

The temperature distributions in the system after 50 years of production for Case 4(a) are shown in Figure 3-67. Comparison of this figure with Figure 3-62 shows that shallow outfield reinjection causes a slight cooling in the shallow production zones.
3.8.3 Case 4(b): Outfield reinjection into the intermediate zone for the laterally open model

Reinjection was made into the intermediate layers between -1146m and -1634m from outfield wells (see Figure 3-45).

The mass production histories for each production area for the no-injection case and for reinjection Case 4(b) are shown in Figure 3-68. This figure shows that for Case 4(b) mass production does not drop as much as for the no-reinjection case. For this case, injection improves the mass flow at production areas A and D more than at the other areas. The reason for this is because shallow production zones are less affected by the intermediate level reinjection than are the deep production zones.
Figure 3-68 Mass production rates from the production areas A, B, C and D for the no-injection case and Case4(b).

The reservoir pressure histories for each production area for the no-injection case and for reinjection Case4(b) are shown in Figure 3-69. Comparison of this figure with Figure 3-63 shows that the mass flow does not decrease for the intermediate reinjection case as much as for the shallow reinjection case (Case4(a)).
Figure 3-69  Reservoir pressures in the production areas A, B, C and D for the no-injection case and Case4(b).

The effect of reinjection on the production enthalpies for this case is shown in Figure 3-70. This figure shows that the areas that only produce from the deep production zones (area A and D) experience a significant enthalpy drop. This is due to the close vertical distance between the reinjection and production zones. At the production areas B and C where there is both shallow and deep production, the enthalpy does not drop for Case(b) as much as for the no-reinjection case. A comparison of Figure 3-61 with Figure 3-71 shows that reinjection into outfield intermediate depth zones prevents lateral recharge. Therefore instead of cold recharge from shallow lateral boundaries, hot recharge flows into the production zones, and thus they produce higher enthalpy fluid.
Figure 3-70 Production enthalpies in production areas A, B, C and D for the no-injection case and Case4(b).
Figure 3-71 Mass flows in the system for the laterally open model, after 50 years of production, for Case4(b) for: (a) cross-section A-A’ and (b) cross-section B-B’.

The temperature distributions in the system after 50 years of production for Case4(b) are shown in Figure 3-72. Comparison of this figure with Figure 3-62 shows that intermediate outfield reinjection causes a slight cooling in the deep production zones.
Figure 3-72  Temperature distributions in the system for the laterally open model, after 50 years of production, for Case4(b) for: (a) cross-section A-A’ and (b) cross-section B-B’.

3.8.4 Case4(c): Outfield reinjection into the deep zone for the laterally open model

Reinjection was applied into the deep zone (layer between -1878m -2121m) at the outfield reinjection blocks (see Figure 3-45).

According to Figure 3-73, the effect of reinjection can be seen after 1 year and the reservoir pressure builds up for about 5 years. For the outfield reinjection scenario, the pressure support in the reservoir resulting from reinjection into the deep layers (Case4(c)) is higher than for the shallow reinjection case (Case4(a) but not as high as for the intermediate reinjection case (Case4(b)) (see Figure 3-64 and Figure 3-69).
Figure 3-73  Reservoir pressures in the production areas A, B, C and D for the no-injection case and Case4(c).

The mass production histories for each production area for the no-injection case and for reinjection Case4(c) are compared in Figure 3-74. The mass flow drops during the first year of production, and then increases up to about the 5th year of production.
As in Case4(a) and Case4(b), since the reservoir pressure does not drop significantly (Figure 3-73), lateral recharge is not observed from the outermost boundaries (see Figure 3-76). Therefore the production enthalpies are higher for Case4(c) than for the no-reinjection case (see Figure 3-75). Among the three cases of outfield reinjection discussed in this section, deep reinjection results in the highest production enthalpies.

Figure 3-74 Mass production rates from the production areas A, B, C and D for the no-injection case and for Case4(c).
Figure 3-75 Production enthalpies in production areas A, B, C and D for the no-injection case and for Case4(c).

Deep outfield reinjection increases the upflow from the bottom of the production zones because it causes a high pressure at the base of the system. Since the fluid that was reinjected into the deep outfield zones sweeps the high energy fluid at the deep zones upwards the temperature of the upflowing fluid is high. Therefore it causes a higher temperature in the both deep and shallow production zones. This temperature difference can be seen from the comparison of Figure 3-77 and Figure 3-62. Hence the enthalpy for Case4(c) is higher than for the no-reinjection case at all production areas. At the production areas A and D where there is only production from the deep zones, a lower enthalpy increase occurs than for the areas B and C. This shows that although deep outfield reinjection increases the hot upflow, deep regions of deep production zones are still affected from the breakthrough of reinjection fluid (see Figure 3-77).
Figure 3-76  Mass flows in the system for the laterally open model, after 50 years of production, for Case4(c) for: (a) cross-section A-A’ and (b) cross-section B-B’.
Figure 3-77 Temperature distributions in the system for the laterally open model, after 50 years of production, for Case4(c) for: (a) cross-section A-A’ and (b) cross-section B-B’, after 50 years of production.
3.8.5 Power output for the outfield reinjection scenario

Figure 3-78 shows a comparison of power output for the no-injection case and the three cases of outfield reinjection. According to this figure all three cases of outfield reinjection results in a higher power output than for the no-reinjection case. Injection into shallow zones causes the least increase in power output. Injection into deep zones gives the greatest improvement in the power output because it results in the highest production enthalpy. The reason for this is deep reinjection supports the reservoir pressure without causing a significant breakthrough of cold reinjection fluid.

![Figure 3-78](image)

Figure 3-78  Power output from the laterally open model for the no-injection scenario and for the injection scenarios Case4(a), Case4(b) and Case4(c).

3.9  Case5: Far-infield reinjection into deep reinjection zones for the laterally open model

In Section 3.8, investigations showed that injecting outfield into deep layers supports the reservoir pressure while preventing early breakthrough of injection
water. Therefore in this section we investigate the effects on the laterally open model of deep far-infield reinjection.

The areal locations of the production and reinjection grid-blocks are shown in Figure 3-31(a). The vertical location of the deep reinjection zone is the layer between -1878m and -2121m, as shown in Figure 3-31(b)-Case (c).

According to the reservoir pressure histories presented in Figure 3-79, for the deep reinjection case, far-infield reinjection results in more pressure support in the reservoir, for all production areas, than outfield reinjection.

Figure 3-79  Reservoir pressures for the laterally open model in the production areas A, B, C and D for the no-injection case (red), Case4(c) (light blue) and Case5 (dark blue).

The mass production histories for each production area are compared for the no-injection case, Case4(c) and Case5 in Figure 3-80. Far-infield reinjection causes a higher mass production than does outfield reinjection.
Figure 3-80 Mass production rates for the laterally open model from the production areas A, B, C and D for the no-injection case (red), Case4(c) (light blue) and Case5 (dark blue).

Reinjection effects on the production enthalpy for the no-reinjection case, Case4(c) and Case5 are compared in Figure 3-81. This figure shows that moving reinjection wells from the outfield to the far-infield increases the production enthalpies at all production areas.
Comparison of Figure 3-76 with Figure 3-82 shows that for the far-infield case (Case 5) there is a large amount of up-flow to the reservoir from the basement of the system, while lateral flow is higher in the Case4(c). Injecting fluid near the bottom of the system and areally between 640m and 1830m from the production wells increases the up-flow of hot water. Although the regions close to the locations of the reinjection wells have lower temperatures (see Figure 3-83), the regions that are far away from the injection wells have higher temperature for Case5 than for Case4(c). Hence the amount of energy that is swept to the production zones by the reinjection fluid for the far-infield case (Case5) is higher than that for the outfield reinjection case (Case4(c)). Therefore the production enthalpies are higher for the far-infield reinjection case (Case5).
Figure 3-82 Mass flows in the system for the laterally open model, after 50 years of production, for Case5 for: (a) cross-section A-A’ and (b) cross-section B-B’.
Figure 3-83 Temperature distributions in the system for the laterally open model, after 50 years of production, for Case5 for: (a) cross-section A-A' and (b) cross-section B-B'.
3.10 Case6: Close-infield reinjection into deep reinjection zones for laterally open model

In this section we investigate the effect of the deep reinjection on the production performance for the case of close-infield reinjection for the laterally open model. The areal locations of production and reinjection grid-blocks are shown in Figure 3-17(a). The areal distance between the production and reinjection wells is 322m. The vertical locations of deep reinjection zones are in the layers between -1878m and -2121m, as shown in Figure 3-17 (b)-Case (c).

According to the comparison of the reservoir pressure histories presented in Figure 3-84, for the deep reinjection case, in the production area B and C there is no significant difference between reinjecting into the far-infield zone (Case5) or the close-infield zone (Case6) for the laterally open model. When reinjection wells are moved from deep far-infield to deep close-infield, reservoir pressures at the deep production zones increase more than those for shallow production zones, because of close proximity between production and reinjection wells. Hence the areas producing only from deep layers (are A and D) shows higher pressures for close infield reinjection case.
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Figure 3-84 Reservoir pressures for the laterally open model in the production areas A, B, C and D for the no-injection case (red), Case5 (light blue) and Case6 (dark blue).

The mass production histories for each production area are compared for the no-injection case, Case5 and Case6 in Figure 3-85. Moving deep reinjection wells horizontally close to the production wells, does not change the mass flow history significantly.
Figure 3-85 Mass production rates for the laterally open model from the production areas A, B, C and D for the no-injection case (red), Case5 (light blue) and Case6 (dark blue).

Reinjection effects on the production enthalpy for the no-reinjection case, Case5 and Case6 are compared in Figure 3-86. This figure shows that moving reinjection wells from far-infield to the close-infield (322m away from production wells) causes a significant decrease in the production enthalpies at all production areas. The reason for this enthalpy drop is thermal breakthrough caused by the very small distance between production and reinjection wells.
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Figure 3-86 Production enthalpies for the laterally open model for the production areas A, B, C and D for the no-injection case (red), Case5 (light blue) and Case6 (dark blue).

Figure 3-87 shows the mass flows in the system for Case6 after 50 years of production. As in Figure 3-82, this figure also shows reinjection increases the upflow to the reservoir from the basement of the system. However because the distance between production and reinjection wells is very short, cold injection water enters into the production blocks.
Figure 3-87 Mass flows in the system for the laterally open model, after 50 years of production, for Case6 for: (a) cross-section A-A’ and (b) cross-section B-B’.

Figure 3-88 shows the temperature distribution in the system for Case6 after 50 years of production. Comparing this figure with Figure 3-83 shows that some regions of the production zones are colder for the close-infield reinjection case (Case6) than those for the far-infield reinjection case (Case5).
Figure 3-88 Temperature distributions in the system for the laterally open model, after 50 years of production, for Case6 for: (a) cross-section A-A’ and (b) cross-section B-B’.
3.11 Power output for the deep reinjection case for the laterally open model

Figure 3-78 shows the comparison of power output for the no-injection case and three cases of deep reinjection. According to this figure all three cases of outfield reinjection result in a higher power output than the no-reinjection case. Injection into the outfield zones causes the least increase in power output. Injection into the close-infield zones gives the largest improvement at early times because of the high mass production. However in the long term, breakthrough effects decrease the output for the close-infield strategy. Hence in the long term, deep far-infield reinjection results in the highest power output for the laterally open model.

Figure 3-89 Power output for the laterally open model for the no-injection scenario and injection scenarios Case4(c), Case5 and Case6.
3.12 Conclusions and discussions

In this chapter the effect of different reinjection schemes in hot water systems was investigated by analysing the production performance, especially the production enthalpy and the power output.

The aim was to decide which strategy is the best for keeping the reservoir pressure and total discharge high and for not reducing the discharge enthalpy by reinjection breakthrough or cold water recharge induced by the pressure drop.

Two types of models were considered: laterally closed boundaries and laterally open boundaries. The results for each type of models are summarised below.

Laterally closed boundaries:

The results presented show that, if there is no-reinjection, strong groundwater recharge occurs into the field induced by the large pressure drop that is caused by production. Because the laterally closed boundary model allows no mass recharge from the sides of the system, a large pressure drawdown occurs in response to production. The large pressure drawdown induces cold groundwater recharge and hence the reservoir enthalpy decreases gradually. Reinjection supports the reservoir pressure and prevents cold water recharge from the groundwater.

The following conclusions summarize the effects on the production performance of close-infield, far-infield and outfield reinjection.

a) Close-infield reinjection:

If reinjection wells are very close to the production wells (322m) and fluid is injected at the same depth as the production zone, then reinjection causes a rapid interference with the production wells. The production enthalpy decreases significantly due to the cold reinjection and this causes a drop in power output. But if reinjection is applied at greater depths than the producing formation, then the effect of thermal breakthrough is less.
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b) Far-infield reinjection:

When reinjection wells are moved away from production wells, to a distance varying between 640m-1830m, thermal breakthrough effects, especially in the shallow and intermediate reinjection cases, are decreased significantly. This scheme, for all reinjection depths, gave improved production enthalpies and resulted in a high power output. The deeper reinjection cases resulted in the highest power output among all the far-infield reinjection scenarios.

c) Outfield reinjection:

Moving reinjection wells from far-infield to outfield (outside the production area, with a closest distance between the production and reinjection wells varying between 939m - 1835m) affected the production enthalpies as follows:

- For the shallow and intermediate level reinjection cases, if the reinjection depth is not the same as the depth of the production zone, then the production enthalpies are similar for both far-infield and outfield reinjection.

- If the reinjection depth is the same as the depth of the production zone, then outfield shallow reinjection results in a smaller thermal breakthrough effect than that which occurs for far-infield reinjection.

- For deep reinjection, if the permeability of the outfield zone is smaller than the far-infield zone, then outfield deep reinjection does not induce a flow of hot water rising from the bottom of the system. Hence the case of far-infield reinjection, with reinjection wells located in permeable zone, gives a higher production enthalpy than the case of deep outfield reinjection.

Laterally open boundaries:

If the model has laterally open boundaries, strong recharge occurs from the sides of the reservoir in response to pressure drawdown. This recharge can be hot or cold depending on the temperature of boundary blocks. In the laterally open model, for the case of no-reinjection, recharge from the side boundary blocks causes a gradual enthalpy drop. The effects for the different reinjection cases are summarized below.
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a) Outfield reinjection:

- Reinjection into shallow and intermediate zones causes thermal breakthrough if there is good communication between the production and reinjection zones.

- Reinjection into the deep zone results in less thermal breakthrough and less cold recharge to the system than for reinjection into the shallow or intermediate zones. Since the deep reinjection zone is vertically close to the production zones, this case prevents a high pressure drop. Because the deep reinjection case gives the highest production enthalpy and a high mass production, this case results in the highest power output.

b) Deep reinjection:

Experiments with the outfield reinjection case showed that the most beneficial strategy for increasing the power output is deep reinjection. Thus the effects of deep reinjection on production performance were investigated for the close-infield and far-infield cases as well. The results show that far-infield reinjection into deep layers supports the reservoir pressure well and results in the highest production enthalpy. Therefore in the long term, this strategy results in highest amount of power output, for the laterally open model.

An overall evaluation of all the reinjection scenarios shows that far-infield reinjection provides the optimum strategy that supports the reservoir pressure without causing an early breakthrough of reinjected fluid.

Reinjection into the deep zone decreases the risk of thermal breakthrough and hence increases the enthalpy and the power output. Thus reinjection applied far-infield and deep provides an optimum strategy for hot-water systems. Since deep reinjection reduces the risk of groundwater contamination and ground surface inflation it gives a good solution for environmental problems as well as providing good field management.
Chapter 4. Generic Liquid-Dominated Two-Phase Systems

4.1 Introduction

In their pre-exploitation or natural state these systems contain all, or mostly, very hot water (i.e. the boiling zones are non-existent or small). However, when production commences, boiling occurs near the feed zones of the wells, caused by large pressure drops. The permeability in the rock surrounding the hot reservoir in such systems may be similar to that inside the reservoir, i.e. there is not necessarily any permeability contrast between the inside (the hot part) and outside (the cold part) of the reservoir. Therefore cold recharge from the sides of the reservoir can easily flow into it. For example in the Wairakei-Tauhara geothermal system, in general permeabilities are high. There are a number of NE–SW trending faults. These faults provide enhanced permeability in the field (Mannington et al. (2004b)). Hence there is substantial recharge that provides natural pressure support to the system (Bixley et al. (2009)).

The production fluid can be high, medium or low enthalpy (Table 1-1) depending on the reservoir permeability and level of fracturing. The high enthalpy version typically has a few major fractures whereas the low enthalpy versions have more general fracturing and more widely spread permeability. The Cerro Prieto and Wairakei fields are examples of medium enthalpy and low enthalpy systems, respectively (Kaya 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. This type of system does not run out of water, as is often the case for vapour-
dominated systems. Also, these systems 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, in contrast to hot water systems. Therefore, from a
reservoir engineering perspective there is no reason to inject infield in two phase
liquid-dominated geothermal systems. In fact injection in two-phase liquid-
dominated geothermal systems has often resulted in adverse thermal breakthrough
and a consequent move of injection outfield. Examples of this type of experience
are Cerro Prieto (Lippmann et al. (2004)) and Tiwi (Sugiaman et al. (2004)).

If the system is more fractured with higher permeability (e.g. Wairakei), production
enthalpies are low - typically not very much above those for hot water. The reason
for this is that when production begins, the pressure does not drop as much and less
boiling occurs. Typically permeabilities for low enthalpy liquid-dominated
systems are high. As a result, cold recharge may flow down into the reservoir from
above or from the sides and extra hot recharge may flow into the reservoir from
below. The balance between hot and cold recharge varies from one system to the
next.

In liquid-dominated two-phase systems the steam fraction may increase during
production. In low enthalpy liquid-dominated systems, in contrast to high enthalpy
ones, the boiling zones are large in extent and are “wet”, i.e. they have a low steam
fraction.

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 (Mannington et al. (2004b)), and there is a shallow
vapour-dominated zone in a pre-dominantly low enthalpy liquid-dominated system.

The large pressure drop at the production wells and the boiling induced in the
reservoir are not undesirable effects from a reservoir engineering point of view. A
high enthalpy mixture of water and steam is an advantage because the conversion
of thermal energy to electricity is more efficient and less separated water has to be
dealt with. However the large drop in reservoir pressure has resulted in some subsidence (Bodvarsson G.S. (1989), Allis (2000)).

The large pressure drop in the reservoir also causes a reduction in surface flows in liquid features and an increased heat flow, mainly from steam, through the surface at some locations. For example in the pre-exploitation term of the Wairakei-Tauhara geothermal system there was a chloride water up-flow from the deep reservoir that mixed with groundwater, and discharged to the surface (e.g. Geyser Valley) (Bromley (2008)). Production decreased the vertical pressure gradient in the reservoir and prevented up-flow from the deeper high-temperature reservoir. Hence the flow to Geyser Valley springs reversed, and the fractures feeding them has became one of the paths by which cool near-surface waters can enter the deep reservoir (Bixley et al. (2009)). Additionally a large area of steam discharge was present at the Karapiti Thermal Area before production start. After production commenced, due to the pressure drop, the steam flow increased. Now the area contains hot ground, numerous fumaroles and steaming craters (Glover et al. (2001)).

The pressure drop at the production wells is in practice buffered by the boiling process. The pressure declines rapidly until boiling occurs, and then the pressure declines more slowly, following the temperature decline. The reasons for the temperature decline are:

- Heat is extracted from the rock matrix to boil off the water, and turn it into steam.
- The cool recharge (mainly water rather than steam) is attracted to the low-pressure zone both from the top and the sides of the reservoir.

Our literature survey of worldwide reinjection experiences, presented in Chapter 1, shows that most part of the energy for electricity production from geothermal systems is from two-phase liquid-dominated systems. Since the total produced mass per 1MWe energy is high in this type of system (higher than for vapour-dominated reservoirs), the quantity of separated and condensed liquid is high. Hence reinjection is not only necessary for achieving sound reservoir management,
having regard to optimum heat recovery and pressure maintenance, but also it is an environmental pre-requisite for the disposal of a large amount of waste water.

In this Chapter Wairakei-Tauhara was chosen as a representative field to investigate the effect of reinjection on liquid-dominated two-phase systems. The reasons for choosing this field as a case study are:

- The Wairakei Tauhara reservoir is a typical two-phase liquid-dominated system (Bixley et al. (2009), Mannington et al. (2004b), Thain and Carey (2009)).

- Since it is the first liquid-dominated geothermal resource in the world to be utilized for electricity production, a long production history is available.

- Since reinjection was carried out only over the last 10 years of production, experiences from this field allow us to observe the effect of reinjection on the production performance and field characteristics (e.g thermodynamic and fluid characteristics of the reservoir and surface features), as well as allowing us to observe the results of production without reinjection.

- An existing computer model of the Wairakei-Tauhara reservoir was available at the University of Auckland (O’Sullivan and Yeh (2007)).
4.2 Model Description

The Wairakei-Tauhara model used in the present study is described in this section. It is a three-dimensional model with an irregular grid structure. Resistivity boundary of the field and locations of Wairakei and Tauhara regions are shown in Figure 4-1.

Figure 4-1. Resistivity boundary and locations of Wairakei and Tauhara regions

The areal and vertical grid structures of the model (312 columns and 32 layers) are shown in Figure 4-2. The top few layers of the model follow the topography of the Wairakei-Tauhara region. Therefore some of the blocks are removed from the upper layers and the model contains a total of 8055 blocks. Small grid-blocks are
used inside the resistivity boundary. Large blocks are included outside the resistivity boundary to allow cold recharge to enter the reservoir.

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**Figure 4-2. Areal and vertical grid structure of the Wairakei – Tauhara Model**

The unsaturated zone is included in the model and thus the model considers the flow of energy, water, and air within the geothermal system. This allows for a better representation of the shallow zone. The unsaturated zone between the ground surface and the water table appears as blocks with a high mass fraction of air, whereas in the saturated zone the mass fraction of air is very low. This approach is an improvement on the standard method of including only the saturated zone (O'Sullivan *et al.* (2001)).
4.2.1 Natural State Model

A pre-exploitation model of the Wairakei-Tauhara system is described in this section. Atmospheric conditions are maintained at the ground surface with 1bar pressure and 20°C temperature. This is implemented in the model by including a very large atmosphere block. This allows water (liquid and vapour) and air to flow up into the atmosphere but only air to flow down into the model. Therefore unlimited surface recharge of the water cannot occur in the air-water model. To implement the infiltration of rainwater, a proportion of the average rainfall into the surface blocks is injected into the surface blocks at a temperature of 20°C. The rate of infiltration is chosen to correspond to 10% of the rainwater being absorbed into the ground (Mannington et al. (2000)). Since three blocks at the south west of the system (grid-block number 964, 965 and 987) represent the lake, a wet atmosphere and a cold temperature (5 °C) is assigned to these blocks.

At the base of the model two types of boundary conditions are applied.

- A mass input into the base of the model (red area in Figure 4-2) and
- A heat input into the base of the model (blue area in Figure 4-2).

The caprock is mainly located at the AP layer (+275masl) and nearby. Surface outflow to hot springs (the grid-blocks bounded with yellow colour in Figure 4-2) is represented in the model by constant mass flow rates from beneath the cap rock.

The Wairakei geothermal reservoir is characterised by high horizontal permeability, low vertical permeability, and low basement and cap-rock permeabilities. The reservoir permeability depends on the amount of faulting. The detailed permeability structure of the model is not reproduced here but typical permeability values of different zones are given in Table 4-1 (Mannington et al. (2004b)).
Table 4-1  Typical permeabilities in the model (Mannington et al. (2004b))

<table>
<thead>
<tr>
<th>Zone</th>
<th>Horizontal permeability, $k_x, k_y$ (x10^-15m^2)</th>
<th>Vertical permeability, $k_z$ (x10^-15m^2)</th>
<th>Porosity (volume fraction) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow zone</td>
<td>200.0</td>
<td>3.0</td>
<td>25</td>
</tr>
<tr>
<td>Cap rock</td>
<td>0.14</td>
<td>0.07</td>
<td>10</td>
</tr>
<tr>
<td>Average production zone</td>
<td>200.0–400.0</td>
<td>5.0–10.0</td>
<td>20</td>
</tr>
<tr>
<td>Fractured production zone</td>
<td>600.0–800.0</td>
<td>15.0–25.0</td>
<td>20</td>
</tr>
<tr>
<td>basement rock</td>
<td>1.0</td>
<td>1.0–5.0</td>
<td>15</td>
</tr>
</tbody>
</table>

The linear relative permeability functions are used in this model with immobile liquid saturation of 0.7, immobile vapour saturation of 0.0, perfectly mobile liquid saturation of 1.0 and perfectly mobile vapour saturation of 0.3 (see Figure 4-3).

Figure 4-3  Relative permeability function used in the Wairakei-Tauhara model.

To improve the fit of the natural state model results to the field data, calibration is carried out. The natural state model simulates the development of the geothermal system over geological time. This involves running the simulation until approximately steady conditions are obtained (typically taking a simulated time in the range of 50,000–100,000 years). The results of this simulation are compared with pre-production measurements within the field. The quantities examined include reservoir temperatures, location of surface outflows, and vapour
saturations. The main parameters adjusted are the permeabilities and the deep inflows (Mannington et al. (2004b)).

The areal temperature distribution in the BH layer (deep production zone) of the natural state model is shown in Figure 4-4. The area bordered with a pink line shows the location of the production area.

![Figure 4-4 Natural-state temperature distribution in the BH layer.](image)

The areal vapour saturation distribution at the top of the reservoir (below caprock), in the AT layer of the natural state model is shown in Figure 4-5. The area bordered with a black colour shows the location of the production area.

![Figure 4-5 Natural-state vapour saturation distribution in the AT layer.](image)
4.2.2 Production model

For the production model of the Wairakei-Tauhara system, the historical data for production and reinjection at the Wairakei field are used as input in the model. The initial conditions for the production model are taken from the natural state model. Further calibration is 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. (2004b)).

After production starts, recharge and surface discharge are affected by the pressure changes. Therefore some boundary conditions and natural discharge parameters described in the natural state model are represented differently in the production model. These differences are;

1- Spring wells that are represented with constant mass flow in the natural state model, are converted into wells on deliverability with DELG option (autough2 (2008)). In this option the deliverability of the production wells has the form

\[
q_m = PI \frac{k}{\nu_f} (p - p_{cut-off})
\]  \hspace{1cm} (4-1)

Where \(q_m\) is the mass flow, \(PI\) is the productivity index, \(k\) is the absolute permeability, \(\nu_f\) is the kinematic viscosity of the fluid, \(p\) is the reservoir pressure and \(p_{cut-off}\) is the trigger pressure at which the well stops flowing. Productivity index values for the spring wells varies between 8.28E-14 and 1.73E-10 m³, the values used in the Wairakei-Tauhara model (O’Sullivan and Yeh (2007)). The DELG option also allows the value of the cut-off pressure to vary with discharge enthalpy.

2- The constant mass input at the base boundary blocks is kept the same as in the natural state model but additional recharge is provided by using the RECH option. When the pressure drops from the initial value, the RECH option allows extra hot recharge to enter the system, through the base layer, in proportion to the pressure drop. The mathematical formula of the following form is used for this option.
Here $q_m$ is the mass flow entering the block at the base of the model, $p$ is the current pressure in the block, $p_o$ is the natural state pressure for the block and $\alpha$ is the recharge coefficient (O’Sullivan (2006)). This option keeps the enthalpy of the recharge fluid the same as the initial enthalpy, so that if the block is initially hot, the recharge is hot and if it is cold, then the recharge is cold. The range of $\alpha$ value that is used to provide additional recharge from the base of the model ranges between 6.00E-09 and 6.97E-05 m$^3$.

3- Lateral recharge from the side boundary blocks is also allowed into the system using the RECH option given in equation (4-2). This allows warm recharge from warm boundary blocks and hot recharge from hot boundary blocks. If the pressure increases at the boundary as a result of injection, then fluid will flow out of the model.

### 4.2.3 Production Scheme

In the model of the Wairakei-Tauhara field that was used for this study production from many Wairakei wells was included.

Production wells are grouped under 5 main production areas,

- Eastern Borefield, (24 wells)
- Western Borefield, (59 wells)
- Pohipi, (5 wells)
- Te Mihi. (31 wells)
- Waist (2 wells)

Figure 4-6 shows the location of these production areas and various well locations.
Figure 4-6 The location of main production areas and various well locations in the Wairakei-Tauhara field (O’Sullivan and Yeh (2006))

The production history of the field from the main production areas is plotted in Figure 4-7. Almost all of the production is taken from between +100 to -500 masl (300 and 900m depth). As it can be seen from Figure 4-7, the major part of the production is from the Western Borefield but with a decreasing mass flow rate throughout the past 40 years. 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. Production from Te-Mihi has gradually increased during the past 13 years.
Figure 4-7 Total production rates for the production areas at Wairakei-Tauhara.

The enthalpy changes for these main production areas are shown in Figure 4-8. As can be seen from this figure, the enthalpy of the Western Borefield has not changed very much over 50 years of production. The Poihipi production area produces dry steam with an average enthalpy of 2770kJ/kg. The enthalpy of the Eastern Borefield and Te Mihi fluctuates through the production period.

Figure 4-8 Production enthalpy histories for the production areas at Wairakei-Tauhara.
4.2.4 Reinjection experience of Wairakei-Tauhara field

In the following sections of this chapter, different reinjection scenarios are compared with the actual injection strategy followed for the Wairakei-Tauhara field (named the BASE model for this study). Therefore in this section, the historical reinjection experience is described.

The areal locations of grid-blocks where reinjection is applied are shown in Figure 4-9 in red. Injection is mainly into the BC (-125masl) and BH (-450masl) layers (shown in red in the vertical column in Figure 4-9). The enthalpy of the reinjection fluid is taken as 564.4kJ/kg which corresponds to 134°C temperature. This is a typical temperature of the separated geothermal water.

![Figure 4-9 Location of reinjection blocks for the BASE model.](image)

A list of the injection wells and their injection rates are shown in Figure 4-10. II62 represents the well WK 62 (shown with black line in Figure 4-10) located in the
Eastern Borefield. This well was mainly used for production. After about 35 years of production a consent for a large injection test was granted and 15% of the separated geothermal water was injected into WK 62 (ContactEnergy (2008)) for a short time.

The two plots for IA308 and IB308 (shown with red spots and a blue line respectively, in Figure 4-10) together represent well WK308. The feed zones for this well correspond to two layers in the model (between -50 and -150mRL). The injection into this well was divided equally between the two reinjection blocks.

![Figure 4-10 Reinjection history for the Wairakei geothermal field (BASE model).](image)

As can be seen in Figure 4-10, most of the reinjection has occurred over the last 10 years. Comparing Figure 4-10 with Figure 4-7 shows that only a small amount of the separated geothermal water has been reinjected.

In the Wairakei Tauhara field until after about 40 years of production, 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 (Bixley et al. (2009)).
As a result of this strategy of no-reinjection for long time followed by a small amount of reinjection, 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. (2004b)).

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

(c) There has been a large drawdown in the reservoir pressure. This has induced an increase in the deep hot recharge to the field. After 30 years of production, the pressure in the deep liquid zone stabilized at about 25 bar (Mannington et al. (2004b), Bixley et al. (2009)).

The areal temperature distribution for the BH layer in the BASE model after 53 years of production is shown in Figure 4-11b. Comparing this figure with Figure 4-11a (pre-production temperature distribution) shows that the 53 years of production with a small amount of reinjection in the last 10 years, caused a very small temperature decrease in the production area (maximum temperature change of 18°C in the area that is close to reinjection zone) of the reservoir (bordered with a pink line).
Figure 4-11  Temperature distributions in the BH layer for: (a) the natural state and (b) the BASE model at year 53.

A comparison of the vapour saturations in the AT layer for the natural state model and for the BASE scenario after 53 years of production are shown in Figure 4-12. The area bordered with black shows the location of the production wells. This figure shows that exploitation caused the formation of extensive new two-phase zones and significantly increased the steam fraction in the existing two-phase zones.

Figure 4-12  Vapour saturation distribution in the AT layer for: (a) natural state and (b) BASE model at year 53.
The recharge into the system from the base and sides is shown in Figure 4-13a and b respectively for the BASE model. It should be noted that the deep recharge shown in Figure 4-13a represents the additional recharge in proportion to the reservoir pressure decline which is calculated by using Equation 4-2. In addition to this, there is deep recharge provided by using a constant mass input (total 478.4 kg/s). The location of these constant mass input are shown in Figure 4-2. These figures show that the amount of recharge from the base and sides of the reservoir has increased and almost stabilised. After reinjection is started its effect can be seen clearly, with the amount of recharge decreasing slightly.

![Figure 4-13 (a) Deep recharge and (b) side recharge for the BASE model](image-url)
4.3 Discussion of Reinjection Scenarios

In this section the scenarios used in an investigation of alternative reinjection strategies for Wairakei-Tauhara are described. They are used to decide which strategy is the best for generic liquid-dominated two-phase systems. Our particular interest is to decide if the reinjection strategy should involve infield reinjection, outfield reinjection or a mixture of both. The impact of different rates of outfield and infield reinjection on production enthalpy, reservoir pressure and temperature, recharge conditions and surface features is discussed. The Wairakei-Tauhara production model described in Section 4.2.2 is used in all cases.

The reinjection scenarios examined in this chapter are summarized in Table 4-2. Here the separated geothermal water (SGW) represents the total amount of water produced from the separators (calculated by subtracting the steam production from the total produced mass). The steam condensate produced from the field is not reinjected.

Table 4-2 Reinjection scenarios

<table>
<thead>
<tr>
<th>Scenario name</th>
<th>Reinjection Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE</td>
<td>Historical situation - no reinjection for a long time, followed by a small amount of reinjection for about the last 10 years</td>
</tr>
<tr>
<td>OUT</td>
<td>Outfield reinjection of 100% of total produced mass</td>
</tr>
<tr>
<td>IN100</td>
<td>Infield reinjection of 100% of SGW</td>
</tr>
<tr>
<td>IN50</td>
<td>Infield reinjection of 50% of SGW</td>
</tr>
<tr>
<td>IN25</td>
<td>Infield reinjection of 25% of SGW</td>
</tr>
</tbody>
</table>
4.4 Outfield reinjection

In this section we discuss an investigation of the effect of outfield reinjection. The outfield reinjection scenario (named OUT in this study) involves reinjecting the waste fluid outside the known reservoir boundaries. Figure 4-14 shows the horizontal (kx and ky) and vertical permeability distribution of the field. The areas used as outfield zones for this study are shown with pink boundaries in Figure 4-14. As can be seen from this figure, the horizontal and vertical permeabilities of the outfield blocks are lower than those for the reservoir blocks. However the permeability of these zones is higher than for other outfield blocks, and thus injection is possible there. There are very low permeability regions between the reservoir and some outfield reinjection zones, indicating a weak permeable connection to the reservoir.
Figure 4-14 (a) horizontal $k_x$, (b) horizontal $k_y$ and (c) vertical ($k_z$) permeability distributions for the BC layer. The locations of the outfield reinjection zones are shown with pink borders.
For the OUT scenario, it was assumed that the amount of steam loss is negligible and the total mass produced from all of the wells is reinjected. The enthalpy of the reinjection fluid was taken as 564.4kJ/kg corresponding to the average temperature of the fluid from the separators of about 134°C.

To decide on the main outfield injection zones, previous modeling studies of the Wairakei-Tauhara model were considered. O’Sullivan and Yeh (2006) concluded that the zones appropriate for outfield injection are grid-blocks 419, 420, 590, 595, 939, 900, 970 and 971 (the grid-blocks shown in Figure 4-15 with bold black borders). However these blocks can accept only a limited amount of reinjection and the amount of liquid to be injected for the OUT scenario is large. For this study we required a larger space for reinjection and therefore we extended the outfield reinjection areas by adding grid-blocks 907, 908, 953, 954, 982, 983, 950, 975, 980, 991, 993 to the reinjection zones used by O’Sullivan and Yeh (2006). As can be seen from Figure 4-14, these areas have the largest permeability of all the outfield blocks, and thus they have a relatively high injectivity.

Figure 4-15 shows how the fluid produced from the different production areas is distributed into the outfield reinjection grid-blocks, shown by the yellow, grey, red, blue and purple areas. The mass produced from the Western Borefield is injected into zones that are shown with blue, while the mass from the Eastern Borefield, Te Mihi, Pohipi and Waist is injected into the red, grey, yellow, purple areas, respectively.

The depths of the reinjection zones also vary according to the permeability of the reinjection layers. As shown in Figure 4-15 waste fluid was injected into the BC, BD and BE layers (between -100masl and -250masl) at the north and north-north west part of the field while it was injected into the BA, BB and BC layers (between 0masl and -150masl) at the north-east and east part of the field. At the two reinjection blocks (shown with dark blue boundary in Figure 4-15) that are close to the infield area, mass is reinjected into the BG and BH layers (-300masl and -500masl).
Figure 4-15 Location of outfield reinjection zones (coloured coded according to the production areas) for the OUT scenario.

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 reinjection flow rate histories are the same as the production flow rate histories since the total mass produced from each production zone is reinjected. Hence the flow rates shown in Figure 4-7 also represent the reinjection rates. The reinjection flows were sub-divided to allow a maximum of about 1kg/s for each 8.84E6 m$^3$ volume of a grid-block. For this calculation the total maximum flow rate for each production area (e.g. 1921 kg/s for Western Borefield as shown in Figure 4-7) is divided up in proportion to the volume of each reinjection block. Therefore a maximum 15kg/s was injected into a small grid-block (e.g. block 415, and 420 in...
Figure 4-15 with dark blue border) while a maximum of 675kg/s was injected into the largest grid-block (eg. block 983 in Figure 4-15).

The fluid produced from each production area is reinjected into several feed zones in each reinjection area (e.g. Figure 4-15 shows that the feed zones at the north part of the field are located in the BC, BD and BE layers). Therefore several layers of each column were assigned as reinjection grid-blocks. Because grid-block 983 is the largest reinjection block, the total fluid produced from the Waist area is injected into this block (into the BC layer) as well as some fraction of fluid from the Eastern Borefield (into the BC layer), and the Western Borefield (into the BA and BB layer) areas. The columns and layers used are shown in Table 4-3.

**Table 4-3  Outfield reinjection grid-blocks used in the OUT scenario**

<table>
<thead>
<tr>
<th>Eastern Borefield</th>
<th>Western Borefield</th>
<th>Te Mihi</th>
<th>Poihipi</th>
</tr>
</thead>
<tbody>
<tr>
<td>grid column layer</td>
<td>grid column layer</td>
<td>grid column layer</td>
<td>grid column layer</td>
</tr>
<tr>
<td>415 #1 BG</td>
<td>980 #1 BC</td>
<td>971 #1 BC</td>
<td></td>
</tr>
<tr>
<td>415 #2 BH</td>
<td>980 #2 BD</td>
<td>971 #2 BD</td>
<td></td>
</tr>
<tr>
<td>420 #1 BG</td>
<td>980 #3 BE</td>
<td>971 #3 BE</td>
<td></td>
</tr>
<tr>
<td>420 #2 BH</td>
<td>975 #1 BC</td>
<td>991 #1 BC</td>
<td></td>
</tr>
<tr>
<td>590 #1 BA</td>
<td>975 #2 BD</td>
<td>991 #2 BD</td>
<td></td>
</tr>
<tr>
<td>590 #2 BB</td>
<td>975 #3 BE</td>
<td>991 #3 BE</td>
<td></td>
</tr>
<tr>
<td>590 #3 BC</td>
<td>950 #1 BC</td>
<td>993 #1 BC</td>
<td></td>
</tr>
<tr>
<td>595 #1 BA</td>
<td>950 #2 BD</td>
<td>993 #2 BD</td>
<td></td>
</tr>
<tr>
<td>595 #2 BB</td>
<td>950 #3 BE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>595 #3 BC</td>
<td>939 #1 BC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>907 #1 BA</td>
<td>939 #2 BD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>907 #2 BB</td>
<td>939 #3 BE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>907 #3 BC</td>
<td>900 #1 BC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>908 #1 BA</td>
<td>900 #2 BD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>908 #2 BB</td>
<td>900 #3 BE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>908 #3 BC</td>
<td>982 #1 BA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>953 #1 BA</td>
<td>982 #2 BB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>953 #2 BB</td>
<td>982 #3 BC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>953 #3 BC</td>
<td>983 #1 BA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>954 #1 BA</td>
<td>983 #2 BB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>954 #2 BB</td>
<td>983 #3 BE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>954 #3 BC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>983 #3 BC</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
First the reservoir pressure histories for the BASE scenario are compared with those for the OUT scenario. Figure 4-16 a, b, c, d and e show this comparison for the Western Borefield, the Eastern Borefield, Te Mihi, the Waist and the Poihipi production areas, respectively. To plot the reservoir pressures, the pressure histories of representative grid-blocks from each production area are used. Table 4-4 shows these representative grid-blocks for each production area.

**Table 4-4 The grid-blocks used to plot pressure histories of each production area**

<table>
<thead>
<tr>
<th>Production Area</th>
<th>Grid-Block</th>
</tr>
</thead>
<tbody>
<tr>
<td>Western Borefield</td>
<td>BC 35</td>
</tr>
<tr>
<td>Eastern Borefield</td>
<td>BA 225</td>
</tr>
<tr>
<td>Te Mihi</td>
<td>AT 20</td>
</tr>
<tr>
<td>Waist</td>
<td>AT 310</td>
</tr>
<tr>
<td>Poihipi</td>
<td>AV 734</td>
</tr>
</tbody>
</table>

According to Figure 4-16 for the Waist and the Poihipi production areas there is no difference between the BASE scenario and the OUT scenario. For the Western Borefield and the Eastern Borefield production areas for about 45 years and for Te Mihi for about 50 years of production there is no difference between the scenarios. Near the end of the production period the BASE scenario shows higher pressures than the outfield reinjection case for these areas. The reason for this is that infield reinjection is implemented in the BASE scenario (see Figure 4-9) for last 10 years of production. Whereas with the OUT scenario there is no infield reinjection and outfield reinjection does not affect the pressure behaviour of the reservoir. This is to be expected as there is no strong hydraulic communication between the outfield reinjection zones and production areas.
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(a) Western Borefield

(b) Eastern Borefield

(c) Te-Mihi

(d) Waist
Figure 4-16  Pressure histories for the BASE scenario and the OUT scenario in: (a) Western Borefield, (b) Eastern Borefield, (c) Te Mihi, (d) Waist and (e) Poihipi.

To see the effect of outfield reinjection on the thermal state of the reservoir, the production enthalpy histories of the BASE scenario are compared with the OUT scenario. Figure 4-17 shows that there is no apparent affect of outfield reinjection on the production enthalpies for any of the production areas.
Figure 4-17  Production enthalpies for the BASE scenario and the OUT scenario in: (a) Western Borefield, (b) Eastern Borefield, (c) Te Mihi, (d) Waist and (e) Poihipi.

The areal temperature distributions for the OUT scenario, after 53 years of production, are shown in Figure 4-18b for the BH layer. Comparing this figure with Figure 4-18a shows that there is little difference in the reservoir temperatures between the BASE scenario and the OUT scenario.
A comparison of the vapour saturations in the AT layer after 53 years of production for the BASE scenario and the OUT scenario is shown in Figure 4-19. The area bordered with black shows the location of the production area. This figure shows that the outfield reinjection does not have any effect on the vapour saturation distribution in the reservoir.
A comparison of recharge into the system from the base and sides for the BASE scenario and the OUT scenario is shown in Figure 4-20a and b respectively. According to this figure recharge from the base does not change when outfield reinjection is implemented. There is no lateral recharge from the side blocks for the OUT case (Figure 4-20b). In fact, since pressure increases at the boundary as a result of injection there is outflow of fluid from the model.

![Figure 4-20](image)

**Figure 4-20** (a) Deep recharge and (b) side recharge for the BASE and OUT scenarios

The results obtained from the OUT scenario show that reinjecting outside the reservoir boundaries, does not affect the reservoir pressure and temperature. Hence outfield reinjection can be considered as a waste water disposal method rather than a technique for maintaining reservoir pressure.
4.5 Infield reinjection

4.5.1 Introduction

Infield reinjection involves reinjecting fluid inside the reservoir boundaries and thus into the zones that have a permeable connection with the production area. With infield reinjection, because of the permeability connection between the production and the reinjection zones, the possibility of the rapid movement of cool injected water along preferred flowpaths between the injection and production wells is a major concern. In this section, results from using the Wairakei Tauhara model to investigate the effect of infield reinjection on two-phase liquid-dominated reservoirs are discussed.

Figure 4-21 Areal and vertical location of infield reinjection.
To decide on the location of infield reinjection blocks, previous work on the Wairakei-Tauhara model was reviewed. According to the studies carried out by O’Sullivan and Yeh (2007), O’Sullivan (2006) and Yeh and O’Sullivan (2009), the preferred locations for infield reinjection are as shown in Figure 4-21.

They are convenient locations in the higher permeability regions of the infield zone, as far as possible from the Wairakei production wells and the future Tauhara production zone. Figure 4-21 shows the columns and layers used as reinjection blocks with colour coding. As for the outfield reinjection scenario, the enthalpy of the reinjection fluid was taken as 564.4kJ/kg.

Based on the locations shown in Figure 4-21, the horizontal distances of production areas from infield reinjection zones are as given in Table 4-5.

<table>
<thead>
<tr>
<th>Production area</th>
<th>Closest and farthest distance from reinjection zone, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern Borefield</td>
<td>0 - 1560</td>
</tr>
<tr>
<td>Waist</td>
<td>970 - 1210</td>
</tr>
<tr>
<td>Poihipi</td>
<td>1245 - 3810</td>
</tr>
<tr>
<td>Te Mihi</td>
<td>1450 - 4700</td>
</tr>
<tr>
<td>Western Borefield</td>
<td>2215 - 2860</td>
</tr>
</tbody>
</table>

Figure 4-22, Figure 4-23 and Figure 4-24 shows the distribution of permeability for horizontal (x and y) and vertical (z) directions respectively for the BC and BH layers.
Figure 4-22 Permeability in the x direction ($k_x$) for: (a) BC layer and (b) BH layer

The areas shown with white boundaries are the locations of infield reinjection zones. These figures show that there is a strong hydraulic connection between the production and infield reinjection zones.

Figure 4-23 Permeability in the y direction ($k_y$) for: (a) BC layer and (b) BH layer
For the infield reinjection scenarios three reinjection rate are considered:

- injection of all the SGW, (IN100)
- injection of 50% of the SGW (IN50)
- injection of 25% of the SGW (IN25)

Here separated geothermal water (SGW) represents the total amount of water produced from separators (calculated by subtracting the steam production from the total produced mass). The steam condensate produced from the field is not reinjected. In the Wairakei Tauhara field this condensate is disposed to the surface (Mannington et al. (2004b)). For the outfield reinjection scenario (OUT), the total produced mass (both steam and water produced from the separators) is injected.

### 4.5.2 Injection of all the separated geothermal water (IN100)

For this case the total separated geothermal water produced from the separators is reinjected into the reservoir. As for the OUT case, the SGW is distributed in proportion to the volumes of the reinjection grid-blocks. A maximum of 50 kg/s is injected into the 50m thick blocks (AV, AX, AZ, BA, BB, BC, BD layers) and
100kg/s is into each of the 100m thick blocks (BG, BH, BI, BJ layers). This operation may require more than one well.

The temperature distribution for the BH layer at year 53 is shown in Figure 4-25b. A comparison of this figure with Figure 4-25a (BASE scenario) shows that the reservoir temperatures are lower for the IN100 scenario. Because the temperature of the reinjected fluid is colder than the reservoir temperature, reinjection causes a temperature decrease in the reservoir.

![Figure 4-25](image)

**Figure 4-25** Temperature distributions in the BH layers at year 53 for: (a) the BASE scenario and (b) the IN100 scenario.

Figure 4-26 shows the temperature differences in the production blocks between the BASE scenario and the IN100 scenario in the BH layers at year 53. In this figure the area bordered with pink line shows the production area and blue gridblocks show the location of the infield reinjection area. As shown in this figure a temperature decrease of up to 55°C occurs in the area that is close to reinjection wells.
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Figure 4-26 Temperature differences (°C) between the BASE scenario and the IN100 scenario in the BH layers at year 53.

The vapour saturation in the AT layer after 53 years of production for the IN100 is shown in Figure 4-27b. Comparison of this figure with BASE scenario (Figure 4-27b) shows that when 100% of the SGW is reinjected into the system the effect of boiling is not seen. Hence the vapour dominated zone is not present at year 53.

Figure 4-27 Vapour saturation distribution in the AT layer at year 53 for: (a) the BASE scenario and (b) the IN100 scenario.
Figure 4-28a shows the vapour saturation history at production regions that are far away from reinjection zones. The gridblocks used for this plot are shown in Figure 4-28b with pink marks. According to Figure 4-28a between years 12 and 20 about 30% vapour saturation develops but after 20 years the effect of boiling disappears. Figure 4-28b shows the vapour saturation distribution in the AT layer at year 15.

Figure 4-28 For the IN100 scenario: (a) Vapour saturation history at the North region of the production area (b) Vapour saturation distribution in the AT layer at year 15.

The effect of reinjection of 100% of the produced liquid on the natural recharge to the reservoir from the base and the sides of the reservoir is shown in Figure 4-29a and b respectively. According to these figures, with the IN100 scenario, recharge from both the base and sides of the system decreases significantly.
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The pressure histories for the BASE scenario, are compared with the pressure histories for the IN100 scenario for the Western Borefield, Eastern Borefield, Te Mihi, Waist and Pohipi in Figure 4-30a,b,c,d,e, respectively. The pressure histories for the grid-blocks shown in Table 4-4 were used. The consequences of strong hydraulic communication between the reinjection and production zones can be seen in Figure 4-30. Because of this communication, infield reinjection supports the reservoir pressure significantly in all the production zones. As expected, the pressure of the Te Mihi area, that is the furthest production area from the infield reinjection zones, is affected least by infield reinjection. Similarly, the highest pressure increase resulting from infield injection occurs in the Eastern Borefield area which is closest to the infield reinjection zone.

Figure 4-29 (a) Deep recharge and (b) side recharge for the BASE and IN100 scenarios
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(a) Western Borefield

(b) Eastern Borefield

(c) Te-Mihi
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Figure 4-30  Pressure histories for the BASE and IN100 scenarios for: (a) Western Borefield, (b) Eastern Borefield, (c) Te Mihi, (d) Waist and (e) Poihipi.

The impact of infield reinjection on reservoir enthalpies is shown in Figure 4-31. According to Figure 4-31a and Figure 4-31b, for the BASE scenario, after about 5 years of production, the production enthalpy for the Western Borefield and the Eastern Borefield increases due to the formation of high vapour saturation zones. Infield reinjection (IN100) decreases the production enthalpy of these areas considerably. The main reason of this enthalpy drop is that the high rate of infield reinjection prevents the formation of high vapour saturation zones (see Figure 4-32). Additionally infield reinjection increases the reservoir pressure and prevents the recharge of hot fluid into to reservoir (Figure 4-29a and b).
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(a) Western Borefield

(b) Eastern Borefield

(c) Te-Mihi
Figure 4-31 Production enthalpy histories for the BASE and IN100 scenarios for: (a) Western Borefield, (b) Eastern Borefield, (c) Te Mihi, (d) Waist and (e) Poihipi.

The vapour saturation distribution in the AT layer at year 5 for the IN100 scenario is shown in Figure 4-32.
Since there is a large pressure drop in the Eastern Borefield area (Figure 4-30b), the production enthalpy for the BASE scenario increases significantly, from 1025kJ/kg to about 1375kJ/kg (see Figure 4-31b). However for the IN100 scenario, the production enthalpy does not increase in this area. In fact it decreases gradually from 1030kJ/kg to 930kJ/kg over about 47 years as a result of the inflow of cold injection fluid. Because the Eastern Borefield area is much closer to the infield reinjection zone, the enthalpy difference between the BASE and IN100 scenarios is much higher for the Eastern Borefield wells than for the Western Borefield wells.

For the first 20 years of production, the Te Mihi area produces medium enthalpy (about 1000kJ/kg) fluid. Because this area is far away from the infield reinjection zone and the production enthalpy is already low, infield reinjection does not cause a discernible enthalpy change for the first 20 years of production (see Figure 4-31c). This area is closed to production between year 20 and 30. After 20 years of production, new production wells were drilled into the field and produced with a higher enthalpy. Hence when the production started again at the 30th year, the BASE scenario produces a high enthalpy fluid (about 1550 kJ/kg). However for the IN100 scenario, the enthalpy of the production fluid does not change very much. As can be seen in Figure 4-31c, in the Te Mihi production area between year 30 and year 53 of exploitation, the BASE scenario produces a high enthalpy fluid fluctuating between 1190kJ/kg and 1750kJ/kg. These fluctuations indicate

Figure 4-32 Vapour saturation distribution in the AT layer at year 5 for the IN100 scenario.
boiling in this production area. Whereas for the IN100 scenario the production enthalpy stays at an almost constant enthalpy of 1050 kJ/kg, which shows there is no boiling for this case.

The Waist production area produces a very small amount of fluid (about 23 kg/s) and only produces for the first 6 years of the production period, and the production enthalpy of this area is not affected by reinjection (see Figure 4-31d).

The production enthalpy for the Poihipi area (see Figure 4-31e) is much lower for the IN100 scenario indicating that this area no longer produces dry steam when 100% infield reinjection is applied.

4.5.3 Injection of 50% of the separated geothermal water (IN50)

As shown by the IN100 scenario, a large amount of fluid reinjected infield may cause premature thermal breakthrough. The BASE scenario results show that, in liquid-dominated reservoirs, when reinjection is limited, a large two-phase zone develops and the vapour saturation of the existing two-phase zones increases. This process enhances the efficient recovery of stored heat in the rock. The two cases presented above (the OUT and IN100 scenarios) represent the extreme cases for infield reinjection. In this section we investigate how the reservoir will be affected when the reinjection rate is decreased to mid-way between the OUT and IN100 scenarios.

Thus for the IN50 scenario half of the mass of total liquid produced from the separators (SGW) is reinjected into the reservoir. To distribute the fluid into the reinjection zones in proportion to the volume of reinjection grid-blocks, a maximum of 25kg/s of fluid were injected into each of the 50m thick infield reinjection grid-blocks (layer AV, AX, AZ, BA, BB, BC, BD) and 50kg/s into each of the 100m thick blocks (layer BG, BH, BI, BJ).

The pressure histories for the IN50 scenario (dark blue) are compared with the pressure histories for the BASE and IN100 (light blue) scenarios in Figure 4-33. The pressure histories for the grid-blocks shown in Table 4-4 were used. As expected this figure shows that decreasing the reinjection flowrate decreases the
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pressure support. For the Western Borefield and Eastern Borefield the reservoir pressures are about the average of those for the BASE scenario and the IN100 scenario.

In the Te Mihi area, somewhat unexpectedly, 50% reinjection decreases the reservoir pressure more than in the BASE scenario. This happens because less boiling occurs for the IN50 scenario than for the BASE scenario (see Figure 4-34). Therefore a slightly larger pressure drop is required to induce the flow through the reservoir to the wells as not so much produced fluid arises from boiling. At the Waist and Poihipi areas the effect of reinjection on the reservoir pressures is quite small.

(a) Western Borefield

(b) Eastern Borefield
Figure 4-33 Pressure histories for the BASE, IN50 and IN100 scenarios for: (a) Western Borefield, (b) Eastern Borefield, (c) Te Mihi, (d) Waist and (e) Poihipi.

A comparison of the vapour saturations in the AT layer after 53 years of production for the BASE scenario and the IN50 scenario is shown in Figure 4-34. This comparison shows that reinjecting only 50% of the SGW significantly decreases
the formation of the two-phase zones. However this decrease is not as great as for the IN100 scenario (see Figure 4-27b).

![Figure 4-34](image)

**Figure 4-34** Vapour saturation distribution in the AT layer at year 53 for: (a) the BASE scenario and (b) the IN50 scenario.

The areal temperature distribution in the BH layer for the IN50 scenario after 53 years of production is shown in Figure 4-35b). Comparing this figure with Figure 4-35a) shows that reinjecting half of the separated water into infield reinjection zones decreases the temperature of the production area. But for this case, temperature drop is not as much as the drop for the IN100 scenario (see Figure 4-25). Thus these figures show that, the IN50 scenario causes less cooling in the production area than the IN100 scenario, as expected.
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Figure 4-35 Temperature distributions in the BH layer at year 53 for: (a) the BASE scenario and (b) the IN50 scenario.

Figure 4-36a and b shows the natural recharge to the reservoir from the base and from the sides of the system respectively. The recharge history for the BASE, IN100 and IN50 scenarios are plotted in this figure. As expected when the rate of infield reinjection is decreased, recharge from the sides and base increases.
The impact of decreasing the amount of reinjection from 100% to 50% of the SGW on the average production enthalpy from the five different production areas is shown in Figure 4-37. This figure compares enthalpy histories for the IN50 scenario with those for the BASE and the IN100 scenarios.

According to Figure 4-37, when the amount of reinjection is decreased, the enthalpy decline due to the effects of reinjected fluid is also decreased. For the Eastern Borefield, Te Mihi and Poihipi areas, even with the 50% reinjection of SGW, the detrimental effect of reinjection is still significant. For the Western Borefield area, after about 8 years of reinjection, the IN50 scenario has an enthalpy midway between the enthalpies for the IN100 and BASE scenarios. However in the long term (after 22 years production) the IN50 enthalpy is very similar to the BASE enthalpy.
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(a) Western Borefield

(b) Eastern Borefield

(c) Te-Mihi
4.5.4 Injection of 25% of separated geothermal water (IN25)

Since infield reinjection causes a significant enthalpy drop even for the injection of only 50% of the SGW (IN50 scenario), at this stage of the study a still lower reinjection rate was considered.

For the IN25 scenario, 25% of the mass of the total SGW is reinjected into the reservoir. As for the previous infield reinjection scenarios, the total amount of reinjection was distributed in proportion to the volume of the infield grid-blocks. A maximum of 12.5kg/s of fluid were injected into each 50m thick infield
reinjection grid-blocks (layer AV, AX, AZ, BA, BB, BC, BD) and 25kg/s into each 100m thick blocks (layer BG, BH, BI, BJ).

Pressure histories for this scenario are compared with the BASE, IN100 and IN50 scenarios in Figure 4-38 for the different production areas. The pressure histories for the grid-blocks shown in Table 4-4 were used. This figure shows, with a low rate of infield reinjection, the reservoir pressure does not drop as much as the BASE scenario, except for the Te Mihi area. The pressure support is considerably smaller than for the IN100 and IN50 scenarios for the Western Borefield and Eastern Borefield. In the Te Mihi area, 25% reinjection does not affect the reservoir pressure significantly for the first 40 years of production. After 40 years, the pressure drops slightly more than for the BASE scenario, because there is less steam in this area than for the BASE scenario (see Figure 4-39). For the Waist and Poihipi areas the pressure history is affected very slightly by the low rate of reinjection.

(a) Western Borefield
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(b) Eastern Borefield

(c) Te-Mihi

(d) Waist
Figure 4-38  Pressure histories for the BASE, IN25, IN50 and IN100 scenarios for: (a) Western Borefield, (b) Eastern Borefield, (c) Te Mihi, (d) Waist and (e) Poihipi.

A comparison of the vapour saturations in the AT layer after 53 years production for the BASE scenario and the IN25 scenario is shown in Figure 4-39. This comparison shows that the vapour saturation for the IN25 scenario is slightly less than that for the BASE scenario.

Figure 4-39  Vapour saturation distribution in the AT layer at year 53 for: (a) the BASE scenario and (b) the IN25 scenario.
The temperature distribution in the BH layer for the IN25 scenario after 53 years of production is shown in Figure 4-40b.

Figure 4-40 shows a very similar distribution to that for the BASE scenario (Figure 4-40a) and thus a low rate of infield reinjection does not change the temperature distribution in the production area significantly.

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 4-41a and b, respectively. The recharge history is plotted for all scenarios. According to these figures, as expected, a lower reinjection rate results in more recharge from the side boundaries and from the bottom of the system. Since there is already a small rate of reinjection at the later times of the BASE scenario, the amounts of recharge from side boundaries are close to each other for the IN25 and BASE scenarios.
Figure 4-41 (a) Deep recharge and (b) side recharge for the BASE, IN25, IN50 and IN100 scenarios.

Figure 4-42 shows the impact of a low rate of reinjection on the average production enthalpy from the five different production areas. To be able to see the differences between this scenario (IN25), and the very high (IN100) and the intermediate (IN50) reinjection scenarios and the BASE scenario, the enthalpy of the four scenarios are plotted together.
Figure 4-42 Production enthalpy histories for the BASE, IN25, IN50 and IN100 scenarios for: (a) Western Borefield, (b) Eastern Borefield, (c) Te Mihi, (d) Waist and (e) Poihipi.

Figure 4-42, shows that, with the low rate of reinjection (IN25) the production enthalpies improve considerably. For the Western Borefield area, the fluctuations in the production enthalpy between that of produced water and dry steam indicates boiling in the reservoir are observed for the IN25 scenario as well as for the BASE scenario (Figure 4-42b). The IN25 scenario produces a slightly lower enthalpy than the enthalpy for the BASE scenario after reinjection effects start to be seen (about 8 years). However in the long term (after 20 years) the reinjection of 25% SGW does not have any detrimental effect on the production enthalpies. In fact after about 40 years the IN25 scenario results in a higher production enthalpy than the BASE scenario. Figure 4-39 also shows that there is slightly higher vapour
saturation for the IN25 scenario than the BASE scenario. The reason for the higher steam fraction in this area and the higher production enthalpy is the smaller amount of cold recharge from the sides and from groundwater with the pressure support of the 25% reinjection of SGW.

For the IN25 scenario, the enthalpy of the Eastern Borefield also improves (Figure 4-42b). Because of the smaller pressure support than for the IN50 scenario, boiling occurs in the reservoir for the IN25 scenario as is indicated by the increase and the fluctuations in enthalpy. In the long term, the high infield reinjection scenario (IN100) gives a slightly lower production enthalpy than for the other scenarios, but there is no significant difference between the BASE, IN25 and IN50 scenarios with regard to production enthalpy values.

The Waist area is not affected by any of the scenarios tried, because production is only carried out for short period of time and the production rate was small (Figure 4-42d).

As can be seen from Figure 4-42c, reinjecting 25% of the SGW (IN25), instead of 50% (IN50), causes a significant improvement in the enthalpy of the production from the Te Mihi area.

For the Pohipi area a low rate of reinjection (IN25) does not affect the production enthalpy for the first 2 years of production (Figure 4-42e). Although after 2 years this area cannot produce dry steam as a result of the effect of infield reinjection. The enthalpy drop is not as high as the drop in the IN50 and IN100 scenarios.

4.5.5 Effect of infield reinjection on surface manifestations

Two-phase geothermal systems may exhibit a wide range of surface geothermal phenomena including hot and boiling springs and streams, geysers, mudpools, fumaroles, hot and steaming grounds etc. Since these surface features have a high intrinsic value, preserving outstanding manifestations is also an important issue to consider in a field development plan. Increasing the reservoir pressure via reinjection could have an impact on the near-surface thermal regime. Reinjecting cold water back into the reservoir may cause a decline in surface manifestations.
since the reinjection fluid invades and condenses the steam zones that lie across the top of the reservoir. In this section, we discuss an investigation of the effect of infield reinjection on the natural surface features of liquid-dominated two-phase systems.

In the natural state of the Wairakei Tauhara geothermal field there was a chloride water upflow from deep Te Mihi and Tauhara. Deep chloride fluids from these regions passed into shallower aquifers, mixed with groundwater, and discharged to the surface. The chloride concentration was highest in relatively undiluted discharges in high-chloride springs at Geyser Valley. Groundwater mixing created more dilute discharges from higher level aquifers at places such as Alum Lakes (Bromley (2008)).

After 1952, production from Wairakei caused a large pressure drawdown in deep aquifers at the Wairakei and the Tauhara regions, and this caused the formation of large steam zones. Because of the pressure drawdown, there was not enough pressure gradient to sustain the flow from the deeper high-temperature reservoir to the overlying groundwater aquifers. Therefore the groundwater has consequently separated hydrologically and became less saline. Some shallow aquifers in South Tauhara have not been affected by deep pressure drawdown associated with Wairakei production, while other shallow aquifers near the Eastern Borefield, the Alum Lakes area and North Tauhara have gradually declined in water level and chloride content with time. (Bromley (2008)).

Prior to exploitation, some surface features (e.g. Waiora Valley) were discharging acid-chloride-sulphate or acid sulphate waters. Since the discharge fluid is not deep chloride fluid, changes due to exploitation occurred more slowly in this area. Exploitation caused boiling in the reservoir. The resulting rising steam increased the heat flow to the surface. Therefore the areas where alkali chloride waters were replaced by steam heated waters, fumaroles and steaming ground has enlarged spatially (Lynne (2008a)).

Another consequence of reservoir pressure drawdown and steam zone expansion was an initial increase in upward steam migration which caused an increase in water temperature in the shallow aquifers. In the Tauhara area this was beneficial
for domestic and commercial heat supply. However after about 1980, declining steam zone pressures have reduced the upflow of steam, and temperatures in steam-heated groundwaters have gradually declined at most locations (Bromley (2008)).

A large area of steam discharge was present at the Karapiti thermal area prior to the exploitation. After production commenced steam flow increased and this enhanced steam-fed geothermal surface features. Numerous new fumaroles and steaming craters formed in Karapiti (Glover et al. (2001), Bromley (2008)).

The representation of surface outflow to hot springs in the Wairakei Tauhara model was explained in Section 4.2.1 and 4.2.2. The locations of surface features in the model are shown in Figure 4-43. In the model, the spring blocks are mostly located in the AR layer (-225masl). To investigate effect of infield reinjection on surface manifestations, the spring blocks in the model are divided into three groups:

1- North: Te Mihi, Alum Lake and Waiora features located in this region (Bromley (2008)). The blocks are shown by an orange bordered area in Figure 4-43.

2- Middle: Represents the Karapiti thermal area (Bromley (2008)). It is shown as a pink bordered area in Figure 4-43.

3- South: The features in Tauhara region are classified under this group. 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 are included in this group (Bromley (2008)). They are shown by the area inside the purple borders in Figure 4-43.
Geysers Valley is one of the major thermal areas in the field that is not represented by spring wells in the model. The dark blue bordered and hatched area in Figure 4-43 shows the location of these features. The output from this area is investigated by observing the thermal properties of the surface grid-blocks, located in this area.

The locations of the infield reinjection wells are shown as blue shaded areas in Figure 4-43.

The effects of three infield reinjection scenarios on surface features are investigated and results are presented as following:

(i) Effect of infield reinjection on spring wells

The effect of infield reinjection on the mass flow from the spring blocks for various reinjection scenarios is shown in Figure 4-44. This figure compares the mass flow history from the spring blocks for the BASE, IN100, IN50 and IN25 scenarios.
Figure 4-44  Mass flows at north, middle and south spring blocks for the BASE, IN25, IN50 and IN100 scenarios.
Figure 4-45 shows the horizontal permeability of the Wairakei Tauhara field in the AR layer, with the locations of the surface manifestations (inside the white borders) and infield reinjection blocks (black spots).

**Figure 4-45** Horizontal permeability distribution in the Wairakei-Tauhara field at AR layer. The location of surface manifestations are shown by white borders and infield reinjection blocks by black spots.

According to Figure 4-44a, a high amount of infield reinjection (IN100) increases the mass flow at the north spring wells (shown with orange borders in Figure 4-43) for the first 9 years of the production due to the pressure support through reinjection (see Figure 4-44a). However after 9 years, a larger mass flow decline occurs for the IN100 scenario than for the BASE scenario. As can be seen from Figure 4-45, there is a high horizontal permeability between the infield reinjection blocks and the north spring wells. This high hydraulic communication between the two zones causes a breakthrough of injected fluid that cools the zone lying over the reservoir and prevents the formation of steam zones in this area.

According to Figure 4-44a, for the intermediate reinjection (IN50) scenario, the mass flow of the north spring wells is affected much less than for the IN100
scenario. For the IN25 scenario there is no apparent difference from the BASE scenario with regard to the mass flows from these wells.

The Karapiti thermal features, that correspond to the middle spring wells (shown with pink borders in Figure 4-43), consisted of steaming ground and fumerolic activity prior to exploitation. Following the extraction of deep thermal fluid, fumarole activity increased in intensity and new fumaroles formed.

As is shown in Figure 4-43, the middle spring block that represents the Karapiti area is within the infield reinjection zone. The spring block is located between the levels of +250masl and +100masl while reinjection is carried out into two different zones of the same column between +150masl and +50masl and between -50masl and -150masl. Figure 4-44b shows that, a very high amount of mass 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 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 4-44b). For the IN25 scenario the mass flow is slightly lower than for the BASE scenario.

The south spring wells (shown with purple borders in Figure 4-43) are located about 2.5 km away from closest production well, and about 1.5km away from closest reinjection zone. According to Figure 4-44c, when production starts, if there is no reinjection, discharge from these wells slightly increases for the first year of production. But after one year, production impacts the outflow adversely and mass flow from these blocks starts to decrease significantly. Therefore although the production wells are more than 2.5km away from the south spring wells, due to the hydraulic communication between the two zones, fluid withdrawal from the reservoir causes a significant decline in surface activity in this area.
The south spring wells cover a large area and represent a large number of the surface manifestations. As expected, reports on these features show that production from Wairakei has had different effects on the surface manifestations for the southern and northern portions of the Tauhara region. The mass discharge from the northern features that are close to the production area (e.g. Spa Park, Otumuheke Stream and Otumuheke Spring) has decreased significantly over the production period. However minimal changes have occurred in the southern features (e.g. Waipahihi-Lake Front and Waipahihi Source spring) since the beginning of the production (Bromley (2008); Lynne (2008b)).

For the IN100 scenario, since the location of the reinjection blocks are far from this area, and there is a low permeability region between the two zones (see Figure 4-45), infield reinjection does not decrease the mass flow of surface features in the southern spring wells Figure 4-44c. Because reinjection prevents the decline of pressure at the south spring blocks, it maintains the surface activity at this area. Figure 4-44c shows that lowering the rate of reinjection from 100% (IN100) to 50% of the SGW (IN50) results in a much smaller changes in the mass flow from the South spring wells. For the very low reinjection scenario (IN25), for the first 23 years of production the IN25 scenario increases mass flow slightly, but in the long term, there is no apparent difference between the mass flows for the BASE and IN25 scenarios.

To see the effect of different rates of infield reinjection on the heat output from the spring wells, the heat flow histories of spring blocks for the BASE, IN100, IN50 and IN25 scenarios are presented in Figure 4-46. According to this figure, the effect of infield reinjection on the heat output from the spring blocks is qualitatively similar to the effect on the mass flow from these blocks.

As can be seen from Figure 4-46a, for the north spring wells, full reinjection into the infield zones (IN100 scenario) maintains the high heat flow for the first five years of production, and then causes a decline in heat flow as a result of the cooling effects of the reinjected fluid. Because the enthalpy from these spring wells still increases despite the high reinjection rate (IN100) (see Figure 4-47a) the heat flow shows some fluctuations and increase until about year 12, then it decreases.
continuously because of the low mass flow (Figure 4-44a). Lowering the reinjection rate from 100% to 50% and 25% of the SGW (the IN50 and IN25 scenarios, respectively) increases the heat flow as a result of allowing more boiling in the reservoir. There is no significant difference in the heat flow from the north spring wells between the BASE and IN25 scenarios.

Figure 4-46b shows that middle spring wells disappear as a result of the high amount of infield reinjection (IN100). However lowering the reinjection rate to 50% and 25% of the SGW (IN50 and IN25) allows these springs to continue.

A high rate of infield reinjection (IN 100) sustains the surface features located at the south part of the field (Figure 4-46c). These springs experience a significant decline if there is no reinjection into the field. A decrease in reinjection rate (IN50 and IN25) causes a decline in the heat flow.
Figure 4-46  Heat flows for the BASE, IN25, IN50 and IN100 scenarios for north, middle and south spring blocks.
The effects of different rates of infield reinjection on the enthalpy from the spring blocks are presented in Figure 4-47a, b and c for the north, middle and south spring wells, respectively.

*Figure 4-47  Production enthalpies for all scenarios for the north, middle and south spring blocks.*
According to Figure 4-47a if there is no infield injection in the field, the enthalpy of the north spring wells increases up to a boiling enthalpy, and this area starts to discharge dry steam after about 10 years of production. The small rate of reinjection during the last 10 years of production does not have a significant effect on the discharge enthalpy from this area for the BASE scenario. For the IN100 scenario the discharge enthalpy increases more slowly and the dry steam enthalpy does not last long. After about 27 years of production, the discharge enthalpy starts to decrease significantly because there is less boiling in the reservoir as a result of pressure maintenance via infield reinjection. For smaller rates of reinjection (the IN50 and IN25 scenarios), reinjection does not effect the production enthalpies of the north spring wells.

For the BASE scenario, at the start the middle spring wells discharge to the surface with a medium enthalpy (Figure 4-47b). But the enthalpy increases in few years to a boiling enthalpy due to the high pressure drop. At the later stages of production, a further pressure drop in the steam zones decreases the steam upflow and causes an enthalpy drop. A high rate of infield reinjection (IN100) stops discharge from this area. For an intermediate rate of reinjection (IN50), the production enthalpies decrease. If the reinjection rate is small (IN25) the steam upflow from the reservoir is only slightly affected, and the enthalpy is slightly less than for the BASE scenario.

According to Figure 4-47c, after about 3 years of production, the enthalpy of the discharge fluid from the south spring wells starts to decrease for the BASE scenario. For the case of high rates of reinjection (IN100), no decline is seen in the enthalpy of the discharging fluid. The reason for this is that, if the reservoir pressure does not drop, the reservoir will have enough pressure gradient for upflow to continue from the deep reservoir to the groundwater aquifers. Hence this hot upflow continues to heat the shallow zones and the temperature of the discharging fluid does not drop.

For the intermediate rate of reinjection (IN50), since there is less pressure support, and hence less upflow, the enthalpy of the south spring wells is lower than the enthalpy of the IN100 scenario (Figure 4-47). A small rate of reinjection (IN25)
does not affect the production enthalpies from these wells, hence there is no significant difference between the IN25 and the BASE scenarios.

**(ii) Effect of infield reinjection on Geyser Valley**

Since the Geysers Valley thermal area is not represented as spring wells in the Wairakei-Taupō model, the output from this area was investigated by considering the flow from the topmost grid-block to the atmosphere. The location of this area is shown by the dark blue bordered and hatched area in Figure 4-43.

The effect of infield reinjection on the mass and heat discharge from the Geyser Valley thermal area is shown in Figure 4-48a, and b respectively. According to these figures whether there is reinjection or not, the mass and heat flow from the Geyser Valley area decreases for about the first 20 years of production. After about 20 years the mass and heat flow continues to decline for the BASE, IN25 and IN50 scenarios. However for the IN100 scenario, reinjection stops the decline and conversely causes a small increase in the mass flow rate at the later stages of production. Therefore for the IN100 scenario (Figure 4-48b), discharge from this area continues with an almost constant heat flow.

Although the IN100 scenario shows sharp changes, until about 35 years of production the higher rate of infield reinjection increases the total mass discharge from Geyser Valley (Figure 4-48a). Conversely, after year 35, the low rate of reinjection (IN25) causes more mass flow than the IN50 scenario. The reason for that is the long term intermediate level of reinjection (IN50) decreases the formation of steam zones more than the IN25 scenario. This causes a decline in the steam zone pressures and reduces the up-flow of steam to the surface. Therefore for the IN50 scenario, there is a lesser amount of mass flow to the surface than for the IN25 scenario (Figure 4-48b).
These investigations show that infield reinjection significantly affects the surface manifestations. According to the results obtained from this part of study, if reinjection zone is inside or very close to the surface features, reinjection prevents boiling in the reservoir, and the steam zones condense. Since it decreases or stops the upflow from reservoir to ground aquifers, infield reinjection causes a decline or disappearance of these features, as shown by the results for the north and middle spring blocks.

Injecting a lesser amount of fluid causes a much smaller changes in the mass and heat flow to the surface features.
If there is less hydraulic communication between the surface manifestations and the reinjection area, because of the long distance or low permeability between these zones, a high rate of reinjection does not decrease the heat and mass flow from the surface manifestations. In fact it results in the maintenance of the flow from these surface features in spite of production since it prevents pressure drawdown without causing cooling (such as for Geyser Valley and the south spring wells).

For the BASE scenario, because of the significant pressure drawdown, the flow from the deep aquifers to the surface features decreases with time. Therefore the chloride content of the surface features decreases and they turn into steam heated features. Infield reinjection increases the reservoir pressure and hence increases the contribution of deep geothermal fluids to the surface features. Therefore it is expected that infield reinjection will maintain the concentration of chloride in the discharge fluid but the temperature of the discharge fluid will be less than for the natural state conditions.

### 4.6 Summary

**Outfield reinjection:** Since 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. The quantity of hot water to be disposed of is large in liquid-dominated two phase systems. Therefore in this type of reservoirs outfield reinjection should be preferred for the disposal of all or part of the separated geothermal fluid.

**Infield reinjection:** Infield reinjection is effective in preventing a large pressure drop in the reservoir. However a large drop in the reservoir pressure causes boiling in the reservoir and hence results in the formation of high vapour saturation zones. Additionally a pressure drop induces strong hot water recharge from the base and side boundaries of the system. Reinjecting into the zones that are connected to the
production area prevents the increase in the steam fraction and causes a drop in the production enthalpies. Since pressure is maintained by cold reinjection, natural hot water recharge to the system is also suppressed. In addition to this, reinjection wells produce a rapid interference with the production areas. The arrival time of reinjection fluid into production zones depends on the distance between production and reinjection zones. But for all production areas, the reinjected water travels to the production zone, and consequently a significant thermal drawdown occurs in the production zones. Reinjecting 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. This scenario appears to be a good infield reinjection strategy.

**Surface features:** Infield reinjection causes a significant decline or disappearance of surface features, if the reinjection zone is inside or very close to the surface features. However, if there is less hydraulic communication between production and reinjection areas, the reinjection fluid prevents both a pressure drop and a decline in the surface manifestations without showing a cooling effect.

If production is carried out without reinjection pressure drop causes boiling in the reservoir. Increased steam saturation due to the boiling results in heat flow to the surface. Therefore steam heated waters, fumaroles and steaming craters form. Decreased reservoir pressure prevents up-flow from the deeper reservoir, and as a result of this the chloride concentration of surface manifestations decreases or vanishes. Reinjection supports the chloride water flow to surface features, but at a lower temperature than in the natural state.
Chapter 5. Generic Vapour-Dominated Two-Phase Systems

5.1 Introduction

Vapour-dominated systems are characterised by a low immobile water fraction so that production wells discharge dry steam. Within the reservoir zone there are high temperatures and comparatively low boiling point pressures.

Thus by their very nature, vapour-dominated two-phase systems have very low permeability surrounding the reservoir. If this were not the case, cold water would flow into the low-pressure vapour-dominated reservoir from the surrounding cool rock. In this type of system, as the reservoir pressure decreases during production more and more of the immobile water boils to form steam which then flows towards the production wells. The water in a vapour-dominated reservoir is not replenished by natural recharge and, after some years of production, parts of the reservoir may run out of immobile water and become superheated (i.e. the pressure of the steam drops below the boiling point).

In this chapter a study of injection in vapour-dominated system is discussed. The Darajat geothermal field is chosen as a case study for two reasons: first it is a typical vapour-dominated geothermal system (Alamsyah et al. (2005), Hadi et al. (2005)) and secondly an existing computer model of Darajat was available at the University of Auckland. The Darajat model has a three dimensional, regular, rectangular grid structure. It was used to represent the natural state and production history of Darajat field. Figure 5-1 shows the areal grid structure of the 3D Darajat model.
In this model an artificial wet atmosphere was assumed as the top boundary to represent groundwater surface. Atmospheric conditions are maintained as 1 bar pressure and 15°C temperature.

At the base of the model two types of boundary conditions are applied. A heat input is applied at the base of the low permeability outer zone blocks (pink area) and constant pressure and saturation conditions are applied at the base of the reservoir blocks (blue area). Studies by O’Sullivan (1990) and McGuinness et al. (1993) showed that these boundary conditions are necessary at the base of a vapour-dominated reservoir. Surface outflow to hot springs is represented in the model by wells operating in deliverability mode, and so the flow to the springs decreases as the reservoir pressures decline. The yellow area shows the locations of the spring blocks.

![Areal grid structure of the 3D Darajat model](image)

**Figure 5-1** Areal grid structure of the 3D Darajat model
The vertical grid structure of the model from North West to South East is shown in Figure 5-2.

Injection into vapour-dominated reservoirs involves complex fluid flow and heat transfer processes including boiling and condensation with strong latent heat effects. Also there is vapour-liquid counter-flow with steam rising and water trickling down. The TOUGH2 geothermal reservoir simulator can model these physical processes, including the highly non-linear phase transitions from vapour to two-phase to liquid conditions and the associated strongly coupled fluid flow and heat transfer effects. However, this capability for simulating the basic processes does not necessarily guarantee realistic predictions for practical injection problems that involve multidimensional flow effects on a broad range of space and time scales (Pruess (1991b)). Therefore to obtain accurate and realistic predictions for modelling injection into vapour-dominated reservoirs, the reservoir parameters and various aspects of model design need to be investigated in detail.

Experiences with modelling vapour-dominated reservoir reported in the literature show that different versions of a model may lead to different predictions, mainly
because of discretization effects, lack of information about relative permeabilities, grid orientation and reservoir heterogeneity.

For example Schroeder et al. (1982) tried various grid spacing on a 1D radial model. Their study shows that models with different sizes of grid blocks produce results with oscillations of different frequency and amplitude. Additionally by trying different relative permeabilities, they showed that the behaviour of their model was strongly affected by the choice of relative permeabilities. Pruess (1994a) and Fitzgerald et al. (1994) showed the sensitivity of the predictions of numerical models to grid orientation and the accuracy of the finite difference scheme.

Therefore it is not easy to set up a good model which produces a realistic prediction of injection effects in vapour-dominated two-phase reservoirs. In order to progress to a good 3D model we decided to first set up a 2D model which allows numerical experiments to be carried out quickly. This 2D model was used to investigate the effect of different model parameters on the predictions of performance and to assess the importance of various modifications to the model. The aim of these experiments was to determine the best choice of model parameters to obtain a model of a vapour-dominated reservoir suitable for the investigation of reinjection effects.

5.2 The 2D Model

5.2.1 Model Description

In order to carry out a large number of numerical experiments very quickly, first a 2D model was set up. It is based on a typical vertical slice through the Darajat Model and is 10 km long, 250 m thick, 4800 m high and consists of 17 layers. The outer zone rock has a very low permeability (0.04-0.16E-15 m²) to prevent cool water flooding the vapour-dominated zone. Similarly a low permeability cap-rock is assigned to the top of the reservoir.
The atmospheric conditions maintained at the ground surface are 1 bar pressure and 15°C temperature. As shown by the modelling studies of O’Sullivan (1990), it is not possible to produce a stable steady state vapour-dominated system by applying a constant mass and energy flow at the base of the model. Increasing the energy flow at the base of the model heats up the reservoir until eventually a liquid dominated two phase system is obtained but with a further increase in energy flow, aimed at establishing a vapour-dominated reservoir, it is not possible to obtain steady state conditions. By considering the stability of a 1-D heat pipe (counter-flow of liquid and steam driven by gravity in a uniform porous medium) McGuinness et al. (1993) showed that a vapour-dominated reservoir has saturation control at depth. Therefore in the 2D model constant pressure and saturation boundary conditions (126 bar pressure and 0.25 vapour saturation) are applied at the base of the reservoir blocks. At the base of the model outside the reservoir a 0.06 W/m² heat input is applied as the basement boundary conditions.

To represent flow from the hot springs a deliverability model is used. For the deliverability option wells produce against a prescribed flowing bottom-hole pressure, \( p_{wb} \), with a productivity index \( PI \) (Pruess et al. (1999)). The mass production rate of phase \( \beta \) from a grid block with phase pressure \( p_{\beta} > p_{wb} \) is given by:

\[
q_{\beta} = \frac{k_{r\beta}}{\mu_{\beta}} \rho_{\beta} PI (p_{\beta} - p_{wb})
\]  

(5-1)

Here \( q \) is mass flow, \( k_r \) is relative permeability for phase \( \beta \), \( \mu \) is viscosity, \( \rho \) is density, \( PI \) is productivity index, \( p \) is fluid pressure and \( p_{wb} \) is the bottom-hole wellbore pressure.

For all production and spring wells the DELG option (autough2 (2008)) is used which allows a discharge proportional to the pressure above some cut-off pressure value. The spring wells have the form:
\[ q_m = PI \frac{k}{\nu_f} (p - p_{\text{cut-off}}) \]  

(5-2)

with

\[ \frac{1}{\nu_f} = \frac{k_{rl}}{\nu_l} + \frac{k_{rv}}{\nu_v} \]  

(5-3)

Here \( q_m \) is the mass flow, \( PI \) is the productivity index, \( k \) is the absolute permeability, \( \nu_f \), \( \nu_l \) and \( \nu_v \) are the kinematic viscosities of the fluid, liquid and vapour, respectively, \( p \) is the reservoir pressure, \( p_{\text{cut-off}} \) is the trigger pressure at which the well stops flowing, \( k_{rl} \) and \( k_{rv} \) are the relative permeabilities for the liquid and vapour phases, respectively.

### 5.2.2 Natural State

The aim of the research described in this section is to set up a 2D natural state model which gives similar initial conditions (pressure, temperature and vapour saturation) to the 3D model. The first model set up, described below, is called Model 1a.

**Model 1a:** A 2D model was set up based on a North West - South East vertical slice through the 3D Darajat model. The vertical grid structure, permeability distribution, heat inputs, deliverability of the spring blocks and boundary conditions from the 3D Darajat model are applied to this 2D model. Three spring blocks are used at locations closest to the springs in the 3D model. Table 5-1 summarizes the rock properties, boundary conditions, deliverability conditions and relative permeability functions used in the steady state Model 1a.
Table 5-1 Parameters used in Model 1a.

<table>
<thead>
<tr>
<th>Rock Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat conductivity : 2.50 W/m²°C</td>
</tr>
<tr>
<td>Specific heat : 1000 J/kg°C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Basement boundary conditions of boundary blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat input: 0.06 W/m²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Basement boundary conditions of the reservoir blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure: 126.0 bar</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Deliverability of spring blocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productivity index : 1.09E-9 m³</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Relative permeability-Linear curves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slr : 0.75</td>
</tr>
</tbody>
</table>

Model 1b: Model 1a produced somewhat different results for pressure, temperature and vapour saturation to those from the 3D Darajat model. To achieve a better match with a simpler permeability structure the following modifications were applied to the springs and the base boundary conditions.

a) Springs

In the 2D model the escape of steam from hot springs is represented by three wells on deliverability under the caprock (the black blocks, bb12, bb19, bb20, shown in Figure 5-3), while there are 15 wells representing hot springs in the 3D model. To obtain similar pressure, temperature and vapour saturation profiles to those for the 3D model, we adjusted the deliverability parameters of the spring wells. It was found to be necessary to decrease the cut-off pressure of the spring wells from 28 bar in the 3D model to 20 bar in the Model 1b in order to obtain similar steady state conditions.
b) Permeability structure

The permeability structure of the original 3D model was simplified to include fewer rock types. The new rock types and distribution are shown in Figure 5-3. The new rock types and their parameters are summarized in Table 5-2.

![Figure 5-3 Simplified rock-type distribution for Model 1b.](image)

Table 5-2  Rock-types and parameters used in Model 1b.

<table>
<thead>
<tr>
<th>Rock Parameters</th>
<th>Rock density $\text{kg/m}^3$</th>
<th>Porosity</th>
<th>Horizontal permeability, $10^{-15} \text{ m}^2$</th>
<th>Vertical permeability, $10^{-15} \text{ m}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>topk</td>
<td>2500</td>
<td>0.1</td>
<td>100.0</td>
<td>1.50</td>
</tr>
<tr>
<td>capk</td>
<td>2500</td>
<td>0.01</td>
<td>0.08</td>
<td>0.04</td>
</tr>
<tr>
<td>andd</td>
<td>2650</td>
<td>0.06</td>
<td>25.0</td>
<td>25.0</td>
</tr>
<tr>
<td>ande</td>
<td>2650</td>
<td>0.06</td>
<td>36.0</td>
<td>36.0</td>
</tr>
<tr>
<td>brcch</td>
<td>2500</td>
<td>0.09</td>
<td>12.50</td>
<td>12.50</td>
</tr>
<tr>
<td>brccm</td>
<td>2500</td>
<td>0.09</td>
<td>2.20</td>
<td>2.20</td>
</tr>
<tr>
<td>side1</td>
<td>2500</td>
<td>0.01</td>
<td>0.16</td>
<td>0.08</td>
</tr>
<tr>
<td>side2</td>
<td>2500</td>
<td>0.01</td>
<td>0.08</td>
<td>0.04</td>
</tr>
<tr>
<td>base1</td>
<td>2500</td>
<td>0.01</td>
<td>3.0</td>
<td>6.0</td>
</tr>
<tr>
<td>base2</td>
<td>2500</td>
<td>0.01</td>
<td>0.72</td>
<td>0.72</td>
</tr>
</tbody>
</table>
c)- **Base conditions**

Here the aim is to assign appropriate basement boundary conditions in order to obtain reservoir pressures, temperatures and saturations typical of a vapour-dominated system.

When we observed the effect of the value of the pressure applied at the base of the system, it was seen that increasing the boundary pressure increases the reservoir pressure up to a maximum value and then a further increase in the deep boundary pressure results in a decreased reservoir pressure (see Figure 5-4). Some experimentation was also tried with different values of basement permeabilities such as 0.70E-15m² and 0.68E-15m². Since the smaller basement permeability restricts the recharge from the bottom of the reservoir, the reservoir pressure is lower for the low basement permeability. However the relationship between reservoir pressure and base pressure was similar for all base permeabilities. It was difficult to achieve steady state conditions for a base pressure greater than 135bar and also it was found that the wet zone encroached into the reservoir more and more for base pressures greater than about 110bar. Figure 5-5 shows the vapour saturation distribution for the natural state conditions of the Model 1b with a basement pressure of 126bar.

![Figure 5-4](image)

**Figure 5-4** Effect of the base boundary pressure on the reservoir pressure for different basement permeabilities.
By numerical experimentation, it was found that values of the base pressure below about 120 bar, give a reservoir state that is more representative of two-phase vapour-dominated systems as the vapour saturations were higher. For higher base pressures the reservoir fluid starts to condense and the liquid saturation increases. Hence the system starts to behave more like a liquid dominated reservoir.

To achieve an approximately uniform vapour saturation in the reservoir and to achieve a good match with reservoir temperatures and pressures from the Darajat model a base pressure of 94.6 bar was used. Figure 5-6 shows the vapour saturation distribution for the model at the natural state conditions for the low (94.6 bar) constant boundary pressure case (Model 1b). For both Model 1a and Model 1b, since the irreducible water saturation is high, the vapour saturation is low in the reservoir.
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Figure 5-6  Vapour saturation distribution for Model 1b (basement pressure is 94.6bar)

The temperature and pressure profiles for Model 1b and for the 3D Darajat model are shown in Figure 5-7. Changing the base boundary pressure from 126bar to 94.6bar in the 2D model, and simplifying the rock structure (as shown in Figure 5-3) gives lower pressure and temperature values at the base of the model, but the profiles for Model 1b match well the pressure and temperature profiles of 3D Darajat model at the reservoir layers. In Model 1b, the vapour saturation distribution is approximately uniform and there is a smaller encroachment of the wet zone for this case, therefore this model was used for the further studies.

Figure 5-7  Comparison of temperature and pressure profiles for the 3D Darajat model and Model 1b (2D)
5.2.3 2D Production and Injection

In the next stage of modelling, production and injection wells were added to Model 1b, and production and injection strategies were investigated. The new model was named Model 2a. As the 3D Darajat model produces mainly from the EE and GG layers, production blocks were assigned to these layers for Model 2a. Three production wells, each producing from two layers, were allocated (shown in Figure 5-3 with red squares). The reinjection wells were located above the production wells (shown in Figure 5-3 with blue squares).

Table 5-3 shows production and injection parameters used in the deliverability option for Model 2a. At first it was decided to assign the same cut-off pressure (20 bar) as for the spring blocks to both feed zones of the production wells. Since the reservoir pressure is higher at the deeper layers this gives a larger pressure difference (between reservoir pressure and cut-off pressure) there and allows the production of a larger amount of fluid from the deeper layers. A maximum steam flow of 20kg/s was assigned for each production block. For the reinjection wells the PINJ option (autough2 notes, 2002) was used which allows a fraction of production from a group of wells to be injected into an injection well. For each reinjection grid-block, 25% of the total steam produced from the two production grid-blocks underneath it was injected.

Table 5-3 Production and injection parameters for Model 2a.

<table>
<thead>
<tr>
<th>production</th>
<th>injection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deliverability option: DELG</td>
<td>Deliverability option: PINJ</td>
</tr>
<tr>
<td>Productivity index : 1.09E-9 m³</td>
<td>Productivity index : 1.09E-9 m³</td>
</tr>
<tr>
<td>Cut-off pressure: 20 bar</td>
<td>Injection enthalpy : 125.7 kJ/kg</td>
</tr>
<tr>
<td>Maximum steam flow: 20 kg/s</td>
<td>Injection fraction :0.25 of steam production</td>
</tr>
</tbody>
</table>

Figure 5-8 shows the steam production rates for this model for the cases of injection (blue) and no-injection. “Separated steam flow” shown in the figure represents produced steam since the field produces only dry steam. According to
this figure there is no significant difference in steam production between the injection and no-reinjection cases.

![Graph showing steam production rates for injection (blue) and no-injection cases for Model 2a](image)

**Figure 5-8  Steam production rates for injection (blue) and no-injection cases for Model 2a**

This result is counter to past experience. As is explained in Chapter 1, field experiences from vapour-dominated systems like Kamojang, Larderello and The Geysers shows that infield reinjection has an important role in maintaining steam production. Therefore it was decided to investigate various modifications to the Model 2.

Changes in the following parameters and aspects of model design were investigated (Table 5-4 shows a catalogue of the models discussed in Section 5.2).

1- Deliverability of the production wells,
2- Relative permeabilities,
3- Vertical permeabilities,
4- Porosities,
5- Reinjection rates,
6- Start time for reinjection,
7- Grid refinement,
8- Embedded radial grids near the wells,
9- Fractured rock model,
10- Nine-point differencing
11- Productivity index

**Table 5-4 Catalogue of 2D models**

<table>
<thead>
<tr>
<th>Model 1a</th>
<th>Described in Section 5.2.1, parameters given in Table 5-1.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1b</td>
<td>Model 1a + simpler rock type distribution + low spring COP*, low basement pressure (94.6 bar)</td>
</tr>
</tbody>
</table>
| Model 2  | a) Model 1b + high COP¹ (20bar) + high MSF² (20kg/s)  
|          | b) Model 1b + high COP¹ (20bar) + low MSF² (5kg/s)  
|          | c) Model 1b + low COP¹ (15bar) + high MSF² (20kg/s)  
|          | d) Model 1b + low COP¹ (15bar) + low MSF² (5kg/s)  |
| Model 3  | Relative permeability curves; (Model 2d with 15% reinjection)  
|          | a) Linear#1  b) Linear#2  c) Grant |
| Model 4  | Model 3c + low vertical permeability |
| Model 5  | Model 3c + low porosity |
| Model 6  | Model 3c + different reinjection rates  
|          | No-injection  b) 25%  c) 35%  d) 50%  e)75%  |
| Model 7  | Model 3c + late start of reinjection |
| Model 8  | refined grid + parameters for Model 3c  
|          | a) one-grid scheme  b) two-diagonal grid scheme |
| Model 9  | Model 3c + embedded radial grid |
| Model 10 | Model 8a + embedded radial grid |
| Model 11 | Model 3c + dual porosity grid  
|          | a) 5% fracture volume  b) 6% fracture volume |
| Model 12 | Very fine grid with the parameters of Model 3c  
|          | a) one-grid scheme  b) two-diagonal grid scheme  c) four-grid scheme |
| Model 13 | Model 12b with 9-point differentiation |
| Model 14 | Model 3c with lower productivity index |
| Model 15 | Model 3c with higher caprock permeability |

1. COP: Cut-off pressure
2. MSF: Maximum steam flow
5.2.3.1 Deliverability of production wells

In Model 2 the production wells operate on deliverability against a prescribed cut-off pressure, with a productivity index PI and maximum steam flow. In this section we investigate the effect of each deliverability parameter individually to see their impact on steam production during reinjection.

First of all the maximum steam flow was decreased from 20 kg/s to 5 kg/s for each well (Model 2b). The results show (see Figure 5-9(a)) that during the first 70 years of production, injection does not have any effect on steam flow, but after that it results in a small increase in steam production.

Secondly, the cut-off pressure was decreased. To decide on a reasonable cut-off pressure a wellbore simulator WELLSIM (Gunn and Freeston (1991)) was run. The pressure loss from the wellhead was calculated as about 1.7bar (using the depth of the deepest production block, the given mass flow rate and the temperature and pressure at the production zone). According to Whittome and Salveson (1990), Berry (1998) and ChevronCorp. (1997)) the operating wellhead pressures for the production wells is 14bar, 15bar and 13.5bar, respectively. Therefore it was decided to decrease the cut-off pressure from 20bar (high cut-off pressure) to the lowest reasonable value of 15bar (low cut-off pressure). The model was re-run with the 20 kg/s maximum steam flow (Model 2c), and the 5 kg/s maximum steam flow (Model 2d). Results are shown in Figure 5-9 (b) and Figure 5-9 (c), respectively. Figure 5-8 and Figure 5-9 (b) show that, for a maximum steam flow of 20 kg/s, whether the cut-off pressure is high or low, reinjection does not have a significant effect on steam production. Whereas Figure 5-9 (c) shows that for the case where both the maximum steam flow and cut-off pressure are lowered injection has a considerable positive effect on steam production.

Since the difference between injection and no-injection cases is the highest for Model 2d the same low cut-off pressure and low maximum steam flow is used in the models discussed in the rest of this section, where further modifications are considered.
Figure 5-9  Steam production rates with
(a) low maximum steam flow, high cut off pressure (Model 2b),
(b) low cut-off pressure, high maximum steam flow (Model 2c),
(c) low cut-off pressure and low maximum steam flow (Model 2d).
Injection (blue) and no-injection (red).

5.2.3.2  Relative permeabilities

Bodvarsson et al. (1980) showed that steam-water relative permeabilities have a
significant impact on the performance of geothermal reservoir models. In this
section our particular interest is to decide on reasonable values for the immobile
liquid and vapour saturations and to choose the shape of the relative permeability
curves that best represent vapour-dominated systems.
Table 5-5 shows the three different relative permeability cases that were tried at this stage of the study and Figure 5-10 shows the corresponding relative permeability curves. The Linear#1 is the relative permeability function which was originally used in the 3D Darajat model and was used for Model 1 and Model 2.

### Table 5-5 Relative permeabilities

<table>
<thead>
<tr>
<th>Relative permeabilities</th>
<th>immobile liquid saturation</th>
<th>immobile vapour saturation</th>
<th>perfectly mobile liquid saturation</th>
<th>perfectly mobile vapour saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear #1</td>
<td>0.75</td>
<td>0.0</td>
<td>1.0</td>
<td>0.25</td>
</tr>
<tr>
<td>Linear #2</td>
<td>0.25</td>
<td>0.0</td>
<td>1.0</td>
<td>0.75</td>
</tr>
<tr>
<td>Grant's Curves</td>
<td>0.1</td>
<td>0.0</td>
<td>1.0</td>
<td>0.9</td>
</tr>
</tbody>
</table>

**Figure 5-10 Relative permeability curves for (a) Linear#1, (b) Linear#2 and (c) Grant's curves.**
In this section of the study Model 2d was used as the base model but 15% of the total produced steam was reinjected, instead of 25%. The reason for using a lower rate of reinjection is because the deliverability parameters used for Model 2d gives a long reservoir life (about 67 years) for the no-reinjection case and 25% reinjection extends the reservoir life until almost 75 years (see Figure 5-9 (c)). In this chapter “reservoir life” is defined as the period that steam production remains at its maximum value. Further modifications in the model may extend the reservoir life still longer and thus may prevent testing effects of long-term reinjection.

Therefore in the later stages of the study, 15% reinjection is used.

The new model, named Model 3a, uses the Linear#1 relative permeability function. For the next model (Model 3b) the Linear#2 relative permeability function was tried.

To be able to compare vapour saturation distributions for the different relative permeability cases, the vapour saturation distribution for Model 1b (given in Figure 5-6), is redrawn in Figure 5-11(a) using a different colour scale. A comparisons of Figure 5-11(a) with Figure 5-11(b) shows that introducing the lower irreducible liquid saturation with the Linear#2 relative permeability function results in higher vapour saturations in the reservoir for Model 3b.
Experiments showed that using different relative permeabilities affects the vapour saturation conditions in the reservoir significantly. However pressure and temperature profiles of the natural state model are not affected when the constant bottom boundary vapour saturation is chosen higher than the perfectly mobile vapour saturation value (when $k_{s}$ is equal to 1.0). Therefore in the study when the Linear#2 function was used, a bottom boundary vapour saturation of 0.75 was applied.

Figure 5-12 compares the steam production rates for the Linear#1 (Model 3a) and the Linear#2 (Model 3b) relative permeability functions, for the cases of injection
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and no-injection. In both cases injection increases steam flow. However with the Linear#2 relative permeability case, the steam flow starts to drop earlier and reinjection prolongs the steam production noticeably. The reason for this early drop of steam production in Model 3b is the different liquid saturation in the natural state conditions of the reservoir. In Model 3a the liquid saturation is 75% in the reservoir whereas for Model 3b it is 25%. Thus there is much more mass available for production in Model 3a than in Model 3b. When production is started, the reservoir pressure starts to decrease and immobile water boils. Thus the vapour saturation increases and buffers a further pressure decline, allowing production of steam for a longer time than for Model 3b.

![Figure 5-12](image)

**Figure 5-12** Steam production rates for injection (blue) and no-injection using the Linear#1 (Model 3a) and the Linear#2 (Model 3b) relative permeabilities.

However as shown in Figure 5-12, for Model 3b (linear#2) the injection case exhibits some sudden increases and decreases in the steam flow. In a study of a 1D vertical model of Larderello, Schroeder et al. (1982) noted that the relative permeability of the two phases is an important parameter for modelling reinjection as it affects both the pressure gradient and liquid propagation through the rock volume. They found out that amplitude and frequency of oscillations depends on
the space discretization used in the model and on the shape of the relative permeability curves. Bordvarsson et al. (1985) tried different relative permeability curves for analysing mobility effects in a two-phase fractured reservoir model, with a 5-spot production-injection well pattern. They suggested that Corey’s curves are not applicable to fractured geothermal reservoirs since the steam flow rate strongly depends on vapour saturation. Figure 5-13 shows Corey’s curves for the same immobile liquid and vapour saturation values as for Grant’s curves, with the parameters given in Table 5-5. According to this figure, the relative permeability for the vapour phase ($k_{rg}$) changes very slowly at low values of vapour saturation but when the vapour saturation is increased, $k_{rg}$ is strongly affected by changes in vapour saturation.

![Corey's Curves](image)

**Figure 5-13 Relative permeability curves for Corey’s curves.**

For Grant’s curve the shape of the gas relative permeability is different. As can be seen in Figure 5-10 (c)), in Grant’s curve, $k_{rg}$ changes quickly at the low values of vapour saturation, but at higher values of vapour saturation it does not change as fast.

At this stage of the study Grant’s curves were applied to Model 3a. This new model was named Model 3c. To obtain similar temperature and pressure profiles to those produced by Model 3a and Model 3b, the constant bottom vapour saturation was chosen at a value 0.9, where $k_{rg}$ is equal to 1.0 (so that the vapour phase is perfectly mobile). Since the immobile liquid saturation is 10%, $k_{rg}$ is
equal 1.0 at $S_v=0.9$, and higher vapour saturation values are obtained in the natural state (see Figure 5-10 (c)). Similar pressure and temperature profiles to those for Model 3a and Model 3b were obtained with this model.

Figure 5-14 shows that using Grant’s curve increases the amount of steam production. This is expected since it allows a higher gas relative permeability than the linear function for the same value of liquid saturation. As shown in Figure 5-14 using Grant’s curve decreases the oscillations and smoothes sharp changes in the steam flow. The effect of reinjection on steam production is similar for both the Linear#2 and Grant’s curve relative permeability functions. Therefore it was decided to use Grant’s curves for the models investigated in the rest of the study.

![Figure 5-14 Steam production rates for injection (blue) and no-injection using the Linear#2 (Model 3b) and Grant’s curves (Model 3c) for relative permeabilities.](image)
5.2.3.3 Vertical permeability

Reservoir Permeability:

The performance of a vapour-dominated reservoir under production depends on how quickly it runs out of liquid water and becomes superheated. One of the factors that affect this process is the recharge of the reservoir zone by steam and water flowing upwards through the reservoir. This effect is in turn controlled by the vertical permeability. In this part of the study anisotropic reservoir permeability is introduced to determine the effect of changes in vertical permeability on steam production.

Using the Model 3c, the vertical permeability of four rock types (brccm, brch, ande, andd) representing the reservoir blocks was decreased by a factor of two and the new model was named Model 4a. This modification increased the temperatures and pressures in the natural state of the system (see Figure 5-15). It resulted in a slight increase in the steam flow for the reinjection case at early times. However after about 50 years the lower vertical permeability case starts to produce less steam than the isotropic permeability case (see Figure 5-16). Since decreasing the vertical permeability does not modify the effect of injection on steam flow this case was not considered further.

Figure 5-15 Comparison of temperature and pressure profiles for Model 3c and Model 4a (with decreased vertical permeability).
Figure 5-16 Steam production rates for injection (blue) and no-injection for Model 3c and Model 4a (with a vertical permeability decrease).

**Basement Permeability**

Natural upflow from the deeper part of the reservoir is strongly affected by the permeability of the basement rock (See Chapter 2, Section 2.3.5). In this part of the study we tried two different vertical permeabilities for the basement rock to see how the effect of reinjection on steam production depends on the deep recharge conditions.

**i) Small basement permeability (Model 4b):** Model 3c was modified by decreasing the vertical permeability of two basement rock types. The vertical permeability of base1 was decreased from 6.0E-15m² to 4.2E-15m² and that for base2 was decreased from 0.72E-15m² to .50E-15m², and new model was named Model 4b. Because there is less upflow from the base of the system, the temperature and pressure in the reservoir decreased significantly. To obtain a good match between the temperature and pressure profiles for Model 3c and Model 4b (see Figure 5-17) the cut-off pressure was increased from 20bar to 29bar. With this modification, the total mass flow from spring wells decreased from 3.22kg/s to 1.125kg/s.
A comparison of the steam flows from Model 3c and Model 4b (with a decreased vertical basement permeability) is shown in Figure 5-18. Because the basement pressure is lower and hence there is less recharge from basement for Model 4b the steam production drops more for this case than for Model 3c. The effect of reinjection on steam production is slightly less for the decreased vertical permeability case (Model 4b).
The effect of reinjection on steam production was not significantly changed by the introduction of low permeability basement rock (Model 4b) and therefore it was not considered further in this study.

**ii) Large basement permeability (Model 4c)**

Starting with Model 3c, the vertical permeability of two basement rock types (base1 and base 2) was modified by increasing the vertical permeability of base1 from 6.0E-15m² to 8.3E-15m² and of base2 from 0.72E-15m² to 1.0E-15m², and new model was named Model 4c. A higher upflow from the base of the system caused higher temperatures and pressures in the reservoir than for Model 3c. Therefore to obtain a good match between Model 3c and Model 4c (see Figure 5-19) the cut-off pressure was decreased from 20bar to 5bar. With this modification, the total mass flow from the spring wells increased from 3.22kg/s to 5.99kg/s.

![Figure 5-19](image)

**Figure 5-19 Comparison of temperature and pressure profiles for Model 3c and Model 4c (with increased vertical basement permeability).**

A comparison of the steam flows for Model 3c and Model 4c (with an increased vertical basement permeability) is shown in Figure 5-20. According to this figure, the high upflow from the base of the reservoir results in a higher steam production in the long term for both the injection and no-injection cases. For the reinjection case of Model 4c small oscillations are observed in the results but the effect of
reinjection on steam production is not significantly different from that for Model 3c.

![Figure 5-20 Steam production rates for injection (blue) and no-injection Model 3c and Model 4c (with an increase in the basement vertical permeability).]

Since over the whole production period, increasing the vertical permeability of the basement rocks did not have significant impact on the effect of reinjection, the higher vertical basement permeability case was not considered further.

### 5.2.3.4 Porosity

For the next model a low reservoir porosity was tried to investigate whether or not the porosity has a significant impact on the effect of reinjection. Starting with Model 3c, the porosity in rock types `brccm` and `brcch` was decreased from 0.09 to 0.07 and for `addd` and `ande` it was decreased from 0.06 to 0.04. This new model was named Model 5. Figure 5-21 shows the effect of decreasing porosity on steam flow for the injection and no-injection cases. According to this figure if the reservoir rocks have lower porosity, the steam flow starts to drop earlier. However decreasing the porosity of the reservoir rocks does not greatly change the effect of
injection on steam flow. Therefore the porosity of the reservoir rock was not changed for the further cases described below.

![Diagram](image)

**Figure 5-21** Steam production rates for Model 5 (decreased reservoir porosity) and Model 3c (original reservoir porosity) for injection (blue) and no-injection.

### 5.2.3.5 Reinjection rates

The amount of reinjected fluid is an important parameter to consider while deciding upon the reinjection strategies. In this section the effect of using different reinjection rates is discussed. To see the effect of reinjection rate on steam flow, four more different reinjection rates were tried with Model 3c (15% reinjection) and compared with the no-injection case. These trials use injection of 25%, 35%, 50%, and 75% of the total produced steam, and are named Model 6a, Model 6b, Model 6c and Model 6d, respectively. Results shown in Figure 5-22 indicate that, for the first three cases and for Model 3c, increasing the reinjection rate extends the lifetime of the reservoir. Although the steam production changes from time to time, overall up to a 50% reinjection rate, a higher reinjection rate results in more
steam production. But for a very high reinjection rate (75%) the duration of maximum steam flow becomes shorter than for the 50% case.

Figure 5-22  Steam production rates for different injection rates

The reason for the decline of steam flow in this case is the proximity of the production and injection wells. As it is shown in Figure 5-23, although oscillations occurs after 80 years of production, in the overall production period the higher reinjection rate results in the higher mass production. However the production enthalpy from the production wells which are closest to the injection wells declines more than for the cases with a lower reinjection rate as a result of the breakthrough of the injected water (see Figure 5-24). Therefore Figure 5-22 shows that in general cold water injection into a vapour-dominated zone enhance the productivity of steam wells. However for the case of a very high injection rate the beneficial effect of injection is lessened.
Figure 5-23  Total mass production rates for different injection rates

Figure 5-24  Flowing enthalpy histories for different injection rates
5.2.3.6 Start time for reinjection

The review of reinjection experiences in Chapter 1 indicates that for some geothermal fields reinjection is commenced after several years of exploitation. This occurred in some cases as a result of environmental problems and the introduction of new regulations, and in other cases in order to prevent further pressure decline or subsidence caused by production, or to moderate a degree of superheat of the produced steam. In this section to investigate the effect of different start times for reinjection on steam production, the following cases are investigated:

(i) reinjection starting at the same time as production (Model 3c),
(ii) reinjection starting after 20 years of production (Model 7).

Figure 5-25 indicates that if injection starts late, the beneficial effect of injection also appear later. These results indicate that an early start of reinjection should be preferred.

Figure 5-25  Steam production rates for no-injection, injection starting with production and injection starting after 20 years of production.
5.2.3.7 Grid refinement

Space discretization effects on reservoir modelling results are well known for immiscible displacement processes Aziz and Settari (1979). These effects arise in two-phase flow because they affect the coupling between fluid flow and heat transfer and alter the phase composition of the flowing two-phase mixture (Pruess (1991b). The discretization of space and time into finite-size intervals introduces inaccuracies because of space and time truncation errors. These generally become smaller when the discretization is refined.

According to Pruess et al. (1979) in problems involving sharp fronts and phase transitions, simulations exhibit oscillating trends that are a consequence of the space discretization. According to Schroeder et al. (1982) the oscillations derive from both the space discretization and from the assumption that at each point of the reservoir the rock and fluid are at all times in thermal equilibrium. They noted that these oscillations occur in all their models of reinjection into regions of the reservoir which are two-phase. According to their study the amplitude and frequency of the oscillations depends on level of space discretization, and they concluded that a finer space discretization will reduce the amplitude and increase the frequency of the oscillations.

In this section, the effects of space discretization on steam production from our 2D model are investigated. The grid blocks in the production region were refined horizontally and vertically, by dividing each grid block into four as shown in Figure 5-26. This new model is named Model 8. The parameters from Model 3c are used in this new model.

Refining the grid blocks and using the same basement boundary conditions, the same heat inputs and the same deliverability parameters as for the coarse model (Model 3c) caused a slight increase in the natural state pressures and temperatures for the fine model (Model 8). The total mass flow from spring wells is also different. It is 3.22 kg/s for the coarse model, while it is 2.87 kg/s for the refined one. Therefore the cut-off pressure for the spring blocks in the fine model was decreased until a better match with the temperature and pressure profile of the
coarse model was obtained. This was achieved with an 18 bar cut-off pressure, and the total production from spring blocks increased to 3.39 kg/s with this new deliverability condition.

![Figure 5-26 Grid structure of the refined model (Model 8)](image)

Since each reservoir block was divided into four, the centre of a coarse block cannot be used as the location of the production and injection wells in the new model. Two different schemes were tried for assigning the wells in the fine model, as shown in Figure 5-27.

1- One-grid-block: left lower grid-block (Model 8a), (Figure 5-27(a)),

2- Two-diagonal grid-blocks: left lower and right upper grid-blocks (Model 8b), (Figure 5-27(b)).
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Figure 5-27 Locations of the wells in the fine grid: (a) one-grid-block and (b) two diagonal grid-blocks

As shown in Figure 5-28 and Figure 5-29, the use of the refined grid results in a slightly faster drop of steam flow. Trials showed that using the two-diagonal grid-blocks scheme gives closer results to those for the coarse grid model (see Figure 5-29). Thus using this scheme diminishes the difference in model behaviour resulting from the difference in the location of the wells.

Figure 5-28 Comparison of steam production rates for the coarse model (Model 3c) and the fine model (Model 8a).
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5.2.3.8 Embedded radial grid near the wells

Near each production well there is a low pressure and high vapour saturation zone which is not possible to represent accurately by a large grid-block. To achieve a more accurate representation of near-well behaviour, it was decided to embed a radial grid within the grid-blocks that contain wells. Embedded radial grids were used with both the coarse model (Model 3c) and the refined model (Model 8a) and named Model 9 and Model 10 respectively.

Figure 5-29  Comparison of steam production rates for the coarse model (Model 3c) and the fine model (Model 8b).

The results shown in Figure 5-28 and Figure 5-29 indicate that mesh refinement produces little change in the results. The results for the two-diagonal grid-blocks scheme (Model 8b) are closer to the results for the coarse model (Model 3c). However Model 8b results show more oscillatory behaviour for the injection case. Since refining the model by dividing each grid block into four does not alter the effect of reinjection in the later stages of the study this refinement is not considered.
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Model 9, Coarse model with embedded radial grids; A radial sub-grid of 26 blocks was embedded in each production block (EE 13, EE 16, EE 19, GG 13, GG 16 and GG 19). The grid structure of the production block is shown in Figure 5-30. The volume of the radially refined section (shown with yellow in Figure 5-30) is half of the total grid-block volume. Within the sub-grid the radial grid-block thickness increases with a 1.20 expansion factor.

Figure 5-30 A block from the coarse model with an embedded radial grid.

Figure 5-31 shows the way connections are defined in each version of the model, with and without an embedded sub-grid.

Figure 5-31 Flow directions through (a) the coarse grid and (b) the embedded radial grid
Figure 5-32 compares results from the coarse model (Model 3c) with those from the same model with an embedded radial grid (Model 9). The results from the model with the embedded grid are significantly different, as the steam production starts to decrease earlier but the decrease is more gradual.

![Figure 5-32 Comparison of steam production rates for the coarse model (Model 3c) and the same model with an embedded radial grid (Model 9) Injection blue, no-injection red.](image)

Because of the better spatial resolution provided by the embedded grid and the more accurate representation of the near-well behaviour, the results produced by the embedded grid model are likely to be more accurate.

**Model 10, Refined model with embedded radial grids:** Similarly an embedded grid consisting of 21 radial blocks was placed into the production blocks of the fine grid model (Model 8a). The grid-block connection scheme shown in Figure 5-31b was used in this case also. The grid structure of the production block is shown in Figure 5-33. The volume of the sub-grid used here is the same as the volume of the first 21 blocks of the grid used in the coarse model (Model 9). The volume of the
radial grid embedded section (shown with blue colour in Figure 5-33) is 31.2% of the total grid-block volume.

![Figure 5-33 Block structure for the refined model with an embedded radial grid](image)

Figure 5-33  Block structure for the refined model with an embedded radial grid

Figure 5-34 (a) compares the steam production rates for the refined model (Model 8a) with those for the refined model with an embedded radial grid (Model 10). Again the embedded grid gives much earlier drop in steam production for both the injection and no-reinjection cases.

Additionally it can be observed from Figure 5-32 and Figure 5-34 that using a radial embedded grid eliminates the oscillations in the steam production for the injection case.
The results of experimentation with Model 9 and Model 10 show that using a radial embedded grid eliminates the oscillations in the model results and produces an earlier and larger decline in steam flow. However the long term behaviour is similar, with or without the radial sub-grid.

5.2.3.9 Fractured rock model

In vapour-dominated systems, fluid transport occurs through a fractured rock matrix and heat from the surrounding rock matrix causes the immobile water in the fractures to boil. In this section we will consider a double porosity model as an alternative to representing the fractured rock matrix as a uniform porous medium.

The idea of representing flow in a fractured porous medium by a “double porosity” model was developed by Barenblatt et al. (1960) and Warren and Root (1963). They assumed that the producing formation is made up of primary (pore) and secondary (fracture) porosity with fractures superimposed on the intergranular primary porosity, constituting a heterogeneous double-porosity medium.
According to the Warren and Root model, global flow in the reservoir occurs only through the connected fracture system. The rock matrix and fractures may exchange fluid (or heat) locally by means of “interporosity flow,” which is driven by the difference in pressures (or temperatures) between the matrix and fractures.

Pruess and Narasimhan (1985) introduced the multiple-interacting continua (MINC) method, as a generalization of the dual-porosity concept. The main transport of fluids takes place through the fractures, while the matrix blocks supply the fluids to the fractures. In this method, each matrix block is divided into a nested sub-domain so that the flow from the matrix to the fracture can be represented in detail. The dimensions of the sub-domain are based upon the distance to the nearest fracture. The transient flow of fluid and heat between matrix and fractures is treated by a numerical method. Pruess and Narasimhan (1985) implemented this formulation in the Integral Finite Difference (IFD) framework used in TOUGH2.

In this part of our study, Model 3c is used as the base model and a MINC partitioning process was used with the parameters for the fractured rock as shown in Table 5-6. This model was named Model 11a.

Table 5-6 The parameters used in the fractured rock model (Model 11a)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of multiple interacting continuia</td>
<td>3</td>
</tr>
<tr>
<td>Type of proximity function</td>
<td>TWO-D</td>
</tr>
<tr>
<td>Matrix block thickness</td>
<td>5.0 m</td>
</tr>
<tr>
<td>Volume fraction of the fracture continuum</td>
<td>5%</td>
</tr>
<tr>
<td>Volume fraction of the matrix continuum</td>
<td>50%, 45%</td>
</tr>
<tr>
<td>Matrix porosity</td>
<td>0.01</td>
</tr>
<tr>
<td>Fracture porosity</td>
<td>0.9</td>
</tr>
</tbody>
</table>

A TWO-D proximity function was chosen (two sets of plane parallel infinite fractures, with arbitrary angle between them). A schematic of the fracture and two matrix continuia is shown in Figure 5-35. The MINC partitioning was applied to eight layers of the reservoir (andd, ande, brcch and brccm rock types) and produced 108×3=324 blocks. The fracture permeability was put equal to the corresponding
permeability in the porous medium model (Model 3c). A matrix permeability 1/10 of the fracture permeability was assigned.

![MINC discretization for the fractured rock model (Model 11a)](image)

**Figure 5-35 MINC discretization for the fractured rock model (Model 11a)**

The MINC grids were initialized with the same initial conditions as the porous model in both the matrix and fractures. Figure 5-36 compares steam production rates for the porous medium model and the fractured medium model. For the fractured medium model, steam production drops earlier than for the porous medium model, for both the injection and no-injection cases. This is to be expected as the MINC model has a lower average porosity (5.45%) compared to an average 7.5% porosity for the standard model. As was seen in Section 5.2.3.4, a lower porosity reduces the available fluid and decreases the steam flow. In the long term, after 70 years of production there is no apparent difference in steam production between the porous medium and fractured medium models.
To assign approximately the same pore volume in both the porous medium and fractured medium models, a new model was set up (Model 11b) with the volume fraction for the fractures increased to 6% and matrix continuum volumes set to 50% and 44%. In this case the average reservoir porosity of the fractured medium model is 6.3%. This value is similar to the average for the porous medium model as most of the reservoir has a porosity of 6% while the remainder has a porosity of 9%. A comparison of the results is shown in Figure 5-37. This figure shows that there is no significant difference in the steam production from the porous medium and fractured medium models. Therefore when the pore volumes of the two types of model are consistent, introducing double porosity into the model does not change the rate of steam production or the effect of injection significantly.

Figure 5-36  Steam production rates for the porous medium model (Model 3c) and fractured medium model (Model 11a). Injection blue, no-injection red.
In the literature strong grid orientation errors have been reported in areal 2-D simulations of steam flooding of petroleum reservoirs. For example, Todd et al. (1972) compared a diagonal grid and a parallel grid in a five-spot simulation, and demonstrated that the predicted recovery performance depends on the grid orientation. The diagonal grid gave more accurate results in waterflood calculations up to an adverse mobility ratio of 10. Coats et al. (1974) simulated steam injection into an oil reservoir and found that grid orientation has a great effect on an unfavourable mobility-ratio displacement. According to Brand et al. (1991) when the mobility of the displacing fluid is greater than the mobility of the resident fluid (an adverse mobility ratio displacement) an instability occurs. The grid orientation effect becomes more and more pronounced as the mobility ratio increases. They demonstrated that the grid orientation effect is a result of coupling between the anisotropic numerical diffusion and the physical instability of the displacement front.

**Figure 5-37** Steam production rates for a porous medium model (Model 3c) and fractured medium model (Model 11b). Injection blue, no-injection red.

### 5.2.3.10 Nine-point differencing
Yanosik and McCracken (1979), Coats and Ramesh (1982), Pruess and Bodvarsson (1983) showed that grid orientation effects can be substantially reduced by means of a "nine-point" approximation, which allows for the possibility of flow along diagonal directions.

Grid orientation effects are aggravated when vertical flow is taken into consideration. Pruess (1991b) and Pruess (1995) simulated injection into vapour-dominated reservoir in a 2D vertical model and compared the shape of the injection plume for parallel and diagonal grid structures, using a conventional 5-point difference approximation. There was a significant difference in the shape of the injection plume between the two cases. For similar models using 9-point differencing, the predictions for the shape of the injection plume are similar, indicating that grid orientation effects have been much reduced.

**Nine-Point Finite-Difference Formulation**

The five-point formulation considers flow between a centre block and the four blocks that are adjacent to its boundaries. In Figure 5-38, point O communicates with E, N, W and S. The nine-point formulation considers these flows as well as the flow between the centre block and the four blocks located at its corners. In this case point O also communicates with NE, NW, SW and SE.

![Figure 5-38 Five and nine-point finite difference approximations (Pruess (1991b))](image-url)
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The basic mass and energy balance equations can be written in the general form:

\[
\frac{Q_n^{s+1} - Q_n^s}{\Delta t} = \frac{1}{V_n} \sum_m A_{nm} F_{nm}^{s+1} + q_n^{s+1} \tag{5-4}
\]

Where \(Q_n^s\) is the mass or energy per unit volume in block \(n\) at time \(s\Delta t\), \(F_{nm}^s\) is the mass or energy flux from block \(n\) to block \(m\), and \(q_n^s\) is the flow to sinks or sources (that is, production or injection wells). The volume of block \(n\) is \(V_n\) and the area connecting block \(n\) to block \(m\) is \(A_{nm}\).

The general expression for 9-point flux differencing is (Forsythe and Wasow (1960); Pruess and Bodvarsson (1983)):

\[
\left( \frac{\sum_m A_{nm} F_{nm}}{V_n} \right)_{9\text{-point}} = \frac{2}{3} \left( \frac{\sum_m A_{nm} F_{nm}}{V_n} \right)_{\text{parallel}} + \frac{1}{3} \left( \frac{\sum_m A_{nm} F_{nm}}{V_n} \right)_{\text{diagonal}} \tag{5-5}
\]

Where the notation “parallel” indicates flux terms arising at the interface areas of the grid, while "diagonal" indicates flux terms across grid block corners.

The volume of the diagonal grid blocks is twice that of the parallel grid-blocks \((V_{n,\text{diagonal}}=2V_{n,\text{parallel}})\). Therefore the proper linear combination, which will yield the nine-point approximation to the equation (5-5) is \(2/3\) the “parallel” version of equation (5-4) plus \(1/6\) the “diagonal” version (Pruess and Bodvarsson (1983)).

Therefore the implementation of the nine-point approximation requires the following steps:

1) An input file is created containing geometric parameters grid volumes, interface areas and distances between grid-blocks appropriate for the conventional five-point method.

2) All interface areas in the “parallel” grid are reduced by a factor 2/3.
3) A list of “diagonal” connections (containing interface areas and distances between grid-blocks) is appended. Then all interface areas are reduced by a factor 1/6 of their original values. The actual distances between the diagonal grid blocks are used.

**Model 12, a very fine 2D model**

The implementation of nine-point differencing requires a regular grid with square grid blocks. Thus before applying nine-point approximation a very fine model with a uniform horizontal and vertical spacing of 100 m was created (Figure 5-39).

![Figure 5-39 Grid structure and permeability distribution of 2D very fine model.](image)

The parameters from Model 8b were used in this new grid structure. By changing the boundary pressure of the bottom of the reservoir from 94.6 to 96.6 bar and using a cut-off pressure of 27.5 bar for the spring wells a good match of natural state conditions was obtained between the coarse model and the very fine model. Spring wells were placed in two-diagonal grid-blocks (left below and right above)
in the refined grid. This new model was named Model 12. Figure 5-40 shows a comparison of temperature and pressure profiles for both models.

![Figure 5-40 Comparison of temperature and pressure profiles for the 2D coarse model (Model 3c) and the very fine model (Model 12).](image)

Because the natural state conditions are adjusted by modifying the cut-off pressure, for the comparison of results from the coarse and refined grids, the location of the production wells becomes important. To obtain a good match between the very fine model and the coarse model, three different grid-block locations were tried for the production and reinjection wells. These schemes are one (left below), two-diagonal (left below and right above) (see Figure 5-27) and four grid-blocks of the refined grids. These models were named Model 12a, Model 12b and Model 12c respectively. Results for these models showed that there is no significant difference between the four-blocks and two-diagonal blocks schemes and they both produce closer results to the coarse model than the one block scheme. Therefore it was decided to use the two-diagonal scheme in the implementation of nine-point differencing. Figure 5-41 shows the comparison of the results of coarse model (Model 3c and fine model (Model 12b).
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Model 13, Implementation of nine-point differencing

Nine-point differencing was implemented in only the reservoir layers (rock types; brccm, brch, andd, ande), as shown in Figure 5-39 by the black outline. This new model was named Model 13. Figure 5-42(a) and (b) shows vapour saturation distribution for five-point and nine-point differencing methods, respectively, after 100 years of production. From these figures it can be observed that for the five-point method injected water flows downward, forming a tall thin plume (Figure 5-42 (a)). Introducing diagonal flow by the nine-point approximation allows the representation of the lateral movement of the wetter injection plume and creates a larger central section of the plume Figure 5-42 (b). Therefore the wetter zone around the production wells supports the pressure of reservoir and allows the production of more steam.

Figure 5-41 Steam production rates for a coarse model (Model 3c) and a very fine model (Figure 12b). Injection blue, no-injection red.
Figure 5-42 Vapour saturation distributions at 100 year for the reinjection case: (a) five-point and (b) nine-point differencing.

Figure 5-43 shows the comparisons of steam flows for models using five-point and nine-point approximations. For the no-injection case there is no difference
between using the five-point or nine-point scheme. For the injection case although this figure does not show much difference between using the 5-point or 9-point approximation, it shows the elimination of spurious oscillations by the use of high order differencing.

![Diagram showing comparisons of steam flows for models using five-point (Model 12b) and nine-point differencing (Model 13).](image)

**Figure 5-43** Comparisons of steam flows for models using five-point (Model 12b) and nine-point differencing (Model 13).

### 5.2.3.11 Lower productivity index

A high productivity index causes the pressure in the production block to be close to the cut-off pressure and thus it results in a high pressure drop in the reservoir. This has the potential to change the boiling process. To test this effect models with different productivity indices were tested.

For Model 14, Model 3c was taken as base model and the productivity index for the production and injection wells was decreased from 1.09E-9m³ to 1.09E-11m³. Figure 5-44 shows that a lower productivity index causes an earlier drop of steam
flow, by about 7 years, for both the injection and no-injection cases. However the steam production drops more gradually. In the long term, for the no-injection case there is no difference in steam production whether the productivity index is low or high. But for the reinjection case, the low productivity index case results in a lower steam production.

Because the lower productivity index reduces the effect of reinjection, Model 14 was not considered for further study.

Figure 5-44 Steam production rates for a high productivity index (Model 3c) and a low productivity index (Model 14). No-injection red, injection blue.
5.2.4 Summary of 2D model investigations

The goal of this section was to provide a good model which reproduces a reasonable prediction of the known effects of reinjection on vapour-dominated two-phase reservoirs. In particular for vapour-dominated reservoirs at Larderello, Kamojang and The Geysers infield reinjection has an important role in maintaining steam production.

The following aspects of the model were investigated and based on the results of the investigations a final model (Model 15) was set up.

(i) Relative permeability:

Three different relative permeability formulae were tried. Using a low value of irreducible liquid saturation and high perfectly mobile vapour saturation increased the vapour saturation in the reservoir and decreased the steam flow. The use of Grant’s curves decreased the oscillations in the production/injection simulations. Therefore Grant’s curves are used in Model 15.

(ii) Porosity and vertical permeability:

Changes in porosity and vertical permeability were tried in the model. The simulation results showed no significant effect, with the relative effect of injection being very weakly affected by changes in these parameters. Hence in Model 15 the porosity and permeability of the reservoir rock were kept same as in Model 3c.

(iii) Reinjection rates:

Five different reinjection rates were tried: 15%, 25%, 35%, 50% and 75% of the total produced steam was reinjected into the reservoir, with an enthalpy of 125.7kJ/kg. Results showed that up to the 50% reinjection rate an increase in reinjection rate causes an increase in steam production. But for the very high (75%) reinjection rate, the steam flow becomes smaller than for the 50% case. This is because the enthalpy of steam from the production wells that are near the injection wells declines as a result of breakthrough of the injected water, and the
beneficial effect of injection is lessened. In Model 15 the low rate of reinjection (15%) was applied.

(iv) Start-time for reinjection:

Trials showed that starting injection at the same time as production gives the best steam output. Therefore in Model 15 production and reinjection were started at the same time.

(v) Double porosity model:

When the pore volume of the porous and fractured models was consistent, introducing a double porosity model to the system, based on a MINC partitioning process did not effect steam production significantly. Also the effect of injection did not depend on whether a porous medium model or a fractured medium model was used. Therefore in Model 15 a porous medium model was used.

(vi) Grid size and orientation:

To analyse the sensitivity of the model results to grid size and orientation, mesh refinement and radial embedded grids near the production wells were tried. Our investigations showed that using a finer grid gives only slightly different results. The steam flow starts to drop from its maximum value sooner but over the long term there is little difference between the coarse grid and fine grid results. Using embedded radial grids near the wells produces different results for the steam flow for the earlier times of production. However the long term behaviour is similar with or without a radial subgrid. In Model 15 the coarse grid was used.

(vii) Nine-point approximation:

Representation of the movement of the injection plume through the diagonal grids as well as parallel grids did not effect steam production significantly but using high order differencing eliminated the spurious oscillations which occur in the injection case. Therefore in Model 15 nine-point differencing was not used.
(viii) Low productivity index:

A lower productivity index causes an earlier drop of steam flow and the steam production drops more gradually. However because it does not have a significant impact on the effect of reinjection, a low productivity index was not used for Model 15.

**Final coarse 2D Model (Model 15):**

According to the result of our investigations for the 2D model, all changes made to Model 3c (e.g. grid refinement, grid orientation methods, nine-point differencing, double porosity models etc) did not result in a significant improvement on the effect of reinjection on reservoir performance. Therefore Model 3c was selected as the basis for a final model. But during all the experimentation an anomalous behaviour was observed and it was decided to make a further change.

Thus to obtain the final model (Model 15) the following changes were applied.

**Model 15. Increased caprock permeability**

Model 3c shows a very low pressure patch in a certain region under the caprock (it can be seen as the two-phase zone in the left upper layers of the models in Figure 5-5, Figure 5-6, and Figure 5-11). This type of behaviour is not likely to occur in real reservoirs, because it is unphysical to have pressures below atmospheric pressure value under the caprock. In order to eliminate it the vertical permeability of the caprock was increased from $0.04E-15m^2$ to $0.08E-15m^2$. Then to obtain similar pressure and temperature profiles to those obtained from Model 3c, the cut off pressure of the spring blocks was increased from 20bar to 25bar. In this case, in the natural state model the mass flow from the spring blocks dropped to 1.71kg/s (while it is 3.21kg/s for Model 3c). Using the slightly higher vertical caprock permeability prolongs the life of the reservoir by about 5 years, for both the injection and no-injection cases (see Figure 5-45).
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Table 5-7 summarizes the rock parameters, boundary conditions, deliverability parameters and relative permeability functions used in the final coarse 2D model. As can be seen from the comparison of this table with Table 5-1 and Table 5-2, the 2D model rock properties such as heat conductivity, specific heat, rock density, porosity and permeability (except vertical permeability of cap rock) of the rock are the same as for Model 1a. The heat input at the base of the boundary blocks is also kept same. The deliverability of the production wells and spring blocks, the relative permeability curves and the basement boundary conditions for the reservoir blocks were modified to obtain the final model (Model 15).

Figure 5-45  Steam production rates for Model 3c and same model with increased vertical caprock permeability (Model 15).
Table 5-7 Parameters used in the Model 15.

<table>
<thead>
<tr>
<th>Rock Parameters</th>
<th>Rock density kg/m³</th>
<th>Porosity</th>
<th>Horizontal permeability, $10^{-15}$ m²</th>
<th>Vertical permeability, $10^{-15}$ m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>topk</td>
<td>2500</td>
<td>0.1</td>
<td>100.0</td>
<td>1.50</td>
</tr>
<tr>
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<td>ande</td>
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</tr>
<tr>
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<td>0.09</td>
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<td>0.16</td>
<td>0.08</td>
</tr>
<tr>
<td>side2</td>
<td>2500</td>
<td>0.01</td>
<td>0.08</td>
<td>0.04</td>
</tr>
<tr>
<td>base1</td>
<td>2500</td>
<td>0.01</td>
<td>3.0</td>
<td>6.0</td>
</tr>
<tr>
<td>base2</td>
<td>2500</td>
<td>0.01</td>
<td>0.72</td>
<td>0.72</td>
</tr>
</tbody>
</table>

Heat conductivity : 2.50 W/m²°C
Specific heat : 1000 J/kg°C

**Basement boundary conditions of boundary blocks**
Heat input: 0.06 W/m²

**Basement boundary conditions of the reservoir blocks**
Pressure: 95.0 bar  Vapour saturation: 0.9

**Deliverability of each spring block**
Productivity index : 1.09E-9 m³  Cut-off pressure: 25 bar

**Deliverability of each production block**
Productivity index : 1.09E-9 m³  Cut-off pressure: 15 bar

**Deliverability of each injection block**
Productivity index : 1.09E-9 m³  Enthalpy : 125.7 kJ/kg
Injection rate : 15% of produced steam

**Relative permeability- Grant’s curves**
Slr : 0.1  Svr: 0.0

Figure 5-46 compares results from Model 3c and Model 15 to show the cumulative effect of the changes made to the caprock permeability and to the production well productivity index. In the final model (Model 15) the drop in steam production starts at the same time as for Model 3c but the steam flow decreases more slowly for both the no-injection and 15% injection cases.
Figure 5-46 Steam production rates for Model 3c and the Model 15 for no-injection and 15% injection cases.

Figure 5-47 compares the no-injection case with cases of 15%, 35%, 50% and 75% injection for the final model. Increasing the reinjection rate up to 50% increases the beneficial effect of reinjection. However increasing the reinjection fraction to 75% does not continue to increase steam production, in fact it gives a lower rate of steam production than for the 35% reinjection case, and after 90 years of production it results in less steam production than for the no-reinjection case.
Figure 5-47 Steam production rates for final model (Model 15), for the no-injection, and 15%, 35%, 50% and 75% injection cases.
5.3 Reinjection Experiments on the 3D Model

5.3.1 Introduction

The aim of the research described in this section is to experiment with a 3D vapour-dominated reservoir model in order to investigate the effects of different production and reinjection strategies. Based on the experience that we obtained from examining the 2D model in section 5.2, we modified the 3D Darajat model which was described in the introduction to this chapter. The modified 3D Darajat model was named 3D-Model 1.

First several of the changes applied to the 2D model in Section 5.2 were applied to 3D-Model 1;

a) As in Section 5.2.2, the rock types of the 3D Darajat model were simplified. Instead of 34, only 10 different rock types was used to represent the ground (topk), caprock (capk), reservoir (brcch, brccm, andd, ande), side boundary blocks (side1, side2) and basement rocks (base1, base2). The parameters for these rocks are the same as those used in the 2D model (shown in Figure 5-7).

b) As in section 5.2.4, to eliminate the anomalous low pressure patch in the model, the vertical permeability of caprock was increased from 0.04 E-15m² to 0.08 E-15m².

c) Figure 5-3 and Figure 5-48 show the vertical and areal (below cap rock) rock structure in the model respectively. The basement boundary conditions were changed to 94.6 bar pressure and 90% vapour saturation as in section 5.2.2.

d) Grant’s curves (see Section 5.2.3.2) were used for the relative permeabilities.
Secondly, to observe the sensitivity of the results to space discretization, the 3D-Model 1 was refined. To limit the number of grid-block in the model and to enable the models to run quickly, only the section shown with the pink boundary in Figure 5-49(a) was refined areally.
Figure 5-49 Areal grid structure of (a) the 3D coarse model (3D-Model 1) and (b) the 3D fine model (3D-Model 2).

The areal grid structure of refined model (named 3D-Model 2) is shown in Figure 5-49(b).

For vertical refinement, the layers located between 1200m and -600m were divided into two. These refined layers include the spring wells, as well as the production and injection wells. The vertical refinement of the 3D fine model (3D-Model 2) is shown in Figure 5-50. In Figure 5-50, the layer where the spring wells are assigned is shown with yellow and the production and injection layers by red and blue, respectively.
### Table 5-50

<table>
<thead>
<tr>
<th>Block name</th>
<th>Cut off pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caprock</td>
<td>14.86 bar</td>
</tr>
<tr>
<td>Spring wells</td>
<td>15.14 bar</td>
</tr>
<tr>
<td>Injection</td>
<td>16.10 bar</td>
</tr>
<tr>
<td>Production</td>
<td>16.65 bar</td>
</tr>
</tbody>
</table>

**Figure 5-50** Vertical grid structure of the 3D-Model 2 and the locations of the spring wells (yellow), injection wells (blue) and production wells.

The areal grid structures of the central zones of the 3D coarse model (3D-Model 1) and the 3D fine model (3D-Model 2) are shown in Figure 5-51(a) and Figure 5-51(b), respectively. In these figures, the location of the spring wells and the production wells are shown with blue and red, respectively. Two of the spring wells in 3D-Model 1 are located outside the refined boundary (see Figure 5-51(a)). The yellow area in Figure 5-51(b) corresponds to the location of these spring wells. In 3D-Model 2 they are re-located into grid-blocks that are inside the refined grid section, shown with the black border in Figure 5-51(b).
Figure 5-51 Areal grid structure of the central zone and the locations of spring wells (blue) and production wells for: (a) 3D-Model 1 and (b) 3D-Model 2.

Table 5-8 summarises the 3D models investigated in this study.

Table 5-8 Catalogue of 3D models

<table>
<thead>
<tr>
<th>3D-Model 1</th>
<th>Parameters described in Table 5-10, grid structure is shown in Figure 5-49a</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D-Model 2</td>
<td>Parameters described in Table 5-10, grid structure is shown in Figure 5-49b</td>
</tr>
<tr>
<td>3D-Model 3</td>
<td>3D-Model 2 + low productivity index</td>
</tr>
<tr>
<td>3D-Model 4a</td>
<td>3D-Model 2 + deeper production zones</td>
</tr>
<tr>
<td>3D-Model 4b</td>
<td>3D-Model 4a + low productivity index</td>
</tr>
<tr>
<td>3D-Model 5</td>
<td>3D-Model 4a + lower flow rates for the production wells</td>
</tr>
</tbody>
</table>

5.3.2 Natural state model

The cut-off pressure for the spring wells used in the original 3D Darajat model was 28 bar. After the modification in rock types, cap rock permeability, relative permeability and basement boundary conditions in the 3D-Model 1, to obtain similar pressure and temperature profiles with 3D Darajat model the cut-off
pressure of the spring wells was increased to 29 bar. Figure 5-52 shows the comparison of pressure and temperature profiles for the 3D Darajat model and 3D-Model 1. The total mass production from the spring blocks is 6.69kg/s for 3D-Model 1, while it is 28.8kg/s for the original 3D Darajat model.

Figure 5-52  Comparison of pressure and temperature profiles for the original 3D Darajat model and for 3D-Model 1.

As can be seen in Figure 5-53, one block in 3D-Model 1 was divided into eight grid-blocks to obtain 3D-Model 2. Because the centre of a coarse block cannot be used as the location of the spring wells, various schemes were tried for assigning these wells into the refined grid structure.

Figure 5-53  Location of spring wells in the 3D fine model (3D-Model 2).
The scheme shown in Figure 5-53 with blue (two diagonal grids for each layer) gave the best match for the natural state pressure and temperature profiles for 3D-Model 1 and 3D-Model 2.

For the production runs investigated in the next section, the production wells were assigned to blocks using this scheme.

Since the cut-off pressure depends on the vertical location of the spring well or production well block, new cut-off pressure values were calculated by using the pressure profile from the natural state for the 3D-Model 1. The cut-off pressures for the refined grid were calculated using interpolation, based on the natural state pressure gradient near the spring blocks in 3D-Model 1. The cut-off pressures were found to be 27 bars for the upper layer and 30.32 bars for the lower layer. These values were used as the first estimates for the cut-off pressures of the refined model. To obtain a better match with the pressure and temperature profiles for 3D-Model 1 the cut-off pressure values for 3D-Model 2 were later decreased to 25.75 and 29 bar for the upper and lower layers, respectively. Figure 5-54 shows the comparison of pressure and temperature profiles for 3D-Model 1 and 3D-Model 2.

![Figure 5-54 Comparison of pressure and temperature profiles for 3D-Model 1 (coarse grid) and 3D-Model 2 (fine grid).](image)

The parameters used in the natural state models for 3D-Model 1 (coarse grid) and 3D-Model 2 (fine grid) are summarised in Table 5-9.
Table 5-9  Natural state parameters used in 3D-Model 1 and 3D-Model 2.

<table>
<thead>
<tr>
<th></th>
<th>3D-Model 1 (coarse)</th>
<th>3D-Model 2 (fine)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring wells</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Productivity index, m³:</td>
<td>1.09E-09</td>
<td>1.09E-09</td>
</tr>
<tr>
<td>Cut-off pressure, bar:</td>
<td>29</td>
<td>25.75, 29</td>
</tr>
<tr>
<td>Relative permeability</td>
<td>Grant's curves :</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Slr : 0.1</td>
<td>Svr: 0.0</td>
</tr>
</tbody>
</table>

In 3D-Model 2, the total mass flow from spring wells is 9.83kg/s in the natural state while it is 6.69 kg/s in 3D-Model 1. To understand the reason for this difference, the models were checked in detail. The side blocks beneath the caprock have a very low vertical (0.08E-15 m²) and higher horizontal (0.16E-15m²) permeability. Because spring wells are located beneath the cap rock, when mass outflow occurs from these wells, the higher horizontal permeability allows lateral recharge from the boundary blocks rather than vertical recharge from the bottom reservoir layers. The vertical refinement in these layers allows more lateral mass flow from the side blocks to the reservoir. Hence the spring wells produce a higher mass flow for 3D-Model 2 than for 3D-Model 1.

5.3.3 Production model

Next production and injection wells were added to both 3D-Model 1 and 3D-Model 2 to compare the behaviour of the models and to investigate different reinjection and production strategies.

In 3D-Model 1 four production wells each producing from two layers were used to simulate steam production (as shown in Figure 5-49). The depth of the production and injection wells is the same as for the 2D model, as described in Section 5.2 and shown in Figure 5-50. The number of reinjection wells is also four. Each injection well was located in the same column as the production well and 400m above the upper production layer. The total maximum steam production is 256kg/s with 32kg/s maximum steam flow assigned to each production block.
To locate the production and injection wells in 3D-Model 2 in blocks corresponding to the well locations in 3D-Model 1, the scheme in Figure 5-53 was used. Thus each well block in 3D-Model 1 was represented by four well blocks in 3D-Model 2. To obtain the 256kg/s maximum steam production in 3D-Model 2, a maximum steam flow of 8kg/s was assigned to each production block.

For production wells, the cut-off pressures were adjusted based on the natural state pressure profile for the reservoir. The pressure gradient of this profile is 1/362.6 bar/m down through the reservoir. In the 3D-Model 1, the cut-off pressure at the upper production layer (+500m) was set at 15bar. Since the elevation difference between upper and lower production layers is 500 meter, the cut-off pressure of the lower production layer was set at 16.38bar. The cut-off pressure values for the production wells were adjusted similarly in 3D-Model 2. Taking the cut-off pressure value at +500m as 15bar, and using the same pressure gradient, the cut-off pressure values of the two upper production layers (layer 29 and 59) were calculated as 14.86bar and 15.14bar, and the two lower production layers (layer 31 and 61) as 16.10bar and 16.65bar (as shown in Figure 5-50). Table 5-10 summarizes the production and injection parameters used in the coarse model (3D-Model 1) and the fine model (3D-Model 2).
Table 5-10  Production and injection parameters used in 3D-Model 1 (coarse model) and 3D-Model 2 (fine model).

<table>
<thead>
<tr>
<th></th>
<th>3D-Model 1</th>
<th>3D-Model 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spring wells</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Productivity index, m³</td>
<td>1.09E-09</td>
<td>1.09E-09</td>
</tr>
<tr>
<td>Cut-off pressure, bar</td>
<td>29</td>
<td>25.75, 29</td>
</tr>
<tr>
<td><strong>Production wells</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of source block</td>
<td>8</td>
<td>32</td>
</tr>
<tr>
<td>Productivity index, m³</td>
<td>1.09E-09</td>
<td>1.09E-09</td>
</tr>
<tr>
<td>Cut-off pressure, bar</td>
<td>15, 16.38</td>
<td>14.86, 15.14, 16.10, 16.65</td>
</tr>
<tr>
<td>Maximum steam flow of each source block, kg/s</td>
<td>32</td>
<td>8</td>
</tr>
<tr>
<td><strong>Injection wells</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Productivity index, m³</td>
<td>1.09E-09</td>
<td>1.09E-09</td>
</tr>
<tr>
<td>Injection rate</td>
<td>15% of produced steam</td>
<td></td>
</tr>
<tr>
<td>Injection enthalpy, kJ/kg</td>
<td>125.7</td>
<td>125.7</td>
</tr>
<tr>
<td><strong>Relative permeability</strong></td>
<td>Grant’s curves: Slr: 0.1 Svr: 0.0</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5-55 shows the comparison of steam production rates for 3D-Model 1 and 3D-Model 2. The results are very similar. Since the space truncation errors are reduced by means of finer grid spacing (Pruess (1991), Pruess and Garcia (2000)), in the following stages of the study 3D-Model 2 was used. According to the experiences reported in the literature (e.g. Schroeder *et al.* (1982)) and our experience with the 2D models, using a fine model will achieve a more accurate representation of reservoir behaviour and will avoid or decrease the spurious oscillations.
5.3.4 Injection Scenarios

5.3.4.1 Scenario Description

Reinjection into vapour-dominated reservoirs requires careful optimisation of the reinjection strategy, to prevent breakthrough and sustain the production of steam. Therefore the amount of fluid injected into reservoir, and the distance between production and reinjection wells are of particular interest.

To observe the effect of amount of reinjected fluid on steam production, different reinjection fractions were tried. As shown in Table 5-11 six scenarios we tried with increasing reinjection fractions and with different locations for reinjection. The enthalpy of reinjection fluid is 125.7kJ/kg.
Table 5-11  Reinjection scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Injection fraction of total steam production</th>
<th>Areal location of injection wells in Figure 5-56</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>15 %</td>
<td>Red grid-blocks</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>35 %</td>
<td>Red grid-blocks</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>50 %</td>
<td>Blue grid-blocks</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>50 %</td>
<td>Green grid-blocks</td>
</tr>
<tr>
<td>Scenario 5</td>
<td>70 %</td>
<td>Grid-blocks with green boundary</td>
</tr>
<tr>
<td>Scenario 6</td>
<td>100 %</td>
<td>Grid-blocks with green + pink boundaries</td>
</tr>
</tbody>
</table>

The vertical locations of the production and reinjection wells for these six scenarios are as shown Figure 5-50. The areal locations of the reinjection blocks for different scenarios are shown in Figure 5-56. The red grid-blocks in Figure 5-56 shows the locations of the production wells. For the scenarios where a low fraction of the total condensate is injected (Scenario 1 and Scenario 2), injection is carried out into the blocks that are right above the production zones. Therefore the red grid-blocks in Figure 5-56 also represent the areal locations of the reinjection wells for Scenario 1 and Scenario 2.

The amount of condensate to be injected for the higher injection fractions (Scenarios 3, 4, 5 and 6) is large. Since the permeability of the layer where reinjection is carried out is low (2.2E-15m²), the injection capacity of these zones is limited. To reinject a large amount of fluid a larger space is required and the number of grid-blocks assigned for reinjection is increased. Thus for Scenario 3 the blue grid-blocks were used for reinjection of 50% of the total produced steam. For the cases of a still higher reinjection fraction, the number of reinjection grid-blocks was further increased. For Scenario 5 the grid-blocks shown with the green boundaries were used, and for Scenario 6 the grid-blocks that are shown with both the green boundaries and the pink boundaries were used (Figure 5-56).

To investigate the effect of reinjection for the case of a longer distance between the production and reinjection wells, Scenario 4 was considered. In this case 50% of the total produced condensate was reinjected into the green grid-blocks that are shown in Figure 5-56. The horizontal distance between the production wells and green grid-blocks is about 375m.
Figure 5-56  Locations of the production wells (red grid-blocks) and the reinjection wells for the injection scenarios.

5.3.4.2  Results

In this section results for the various reinjection scenarios are presented. The parameters used in this model for all the scenarios are as given in Table 5-10 (3D-Model 2 (fine) section).

Results for the scenarios with the lower reinjection rates are shown in Figure 5-57. According to the figure, applying 15% reinjection (Scenario 1) to the reservoir extends the reservoir life and causes it to produce a higher steam flow than the no-injection case. For up to 50% reinjection (Scenario 3) an increase in injection rate causes an increase in steam production.
Figure 5-57 Steam production rates for the no-injection case and for Scenarios 1, 2 and 3 (low reinjection rates).

For a 70% injection rate (Scenario 5) the duration of production at the maximum steam flow is a small amount shorter than for the 50% case (Figure 5-58). For 100% reinjection (Scenario 6), steam production is lower than for 50% and 70% reinjection. Similar behaviour was observed when the same reinjection scenarios were applied to 3D-Model 1 (3D coarse model).
Figure 5-58  Steam production rates for the no-injection case and for Scenarios 3, 5 and 6 (high reinjection rates).

The reason for the decrease in steam production for the cases with a high reinjection rate is the proximity of the production and injection wells. The enthalpy of steam from the production wells that are near the injection wells declines as a result of breakthrough of the injected water. As was observed in Section 5.2.3.5 a higher rate of reinjection results in a higher mass production rate, however it causes the highest enthalpy drop. Therefore steam production decreases with the high injection rate. Figure 5-57 and Figure 5-58 shows that in general cold water injection into vapour-dominated zones enhances the productivity of steam wells. However for the case of a very high injection rate the beneficial effect of injection is lessened.

To observe the effect of the location of the reinjection wells on steam production in vapour-dominated reservoirs Scenario 3 and Scenario 4 were compared. As stated in Table 5-11, 50% reinjection is applied at the blue grid-blocks in Figure 5-56 for Scenario 3, and for Scenario 4 the same rate of reinjection is applied at the green grid-blocks, which are about 375m far away, horizontally, from the production wells. Figure 5-59 shows that at early times, reinjecting right above the production
wells (Scenario 3) causes a slightly higher steam production rate than injecting infield but further away from the production area (Scenario 4). However in the long term, reinjecting further away leads to a higher rate of steam production.

Figure 5-59 Steam production rates for the no-injection case, Scenario 3 and Scenario 4.

Figure 5-60 shows the vapour saturation distributions after 100 years of production for Scenario 3 and Scenario 4, on the vertical cross-section A-A' in Figure 5-56. The white rectangles and the rectangles with red boundaries show the location of the production and reinjection wells, respectively. As can be seen from the figure, for Scenario 3 the vapour saturation around the production blocks is lower than for Scenario 4. Increasing the distance between production and reinjection zones by distributing reinjection wells around the production wells diminishes the breakthrough of injected water and causes a higher rate of steam production.
Figure 5-60  Vapour saturation distributions after 100 years of production for: (a) Scenario 3 and (b) Scenario 4.
5.3.4.3 Lower productivity index (3D-Model 3)

In this section case of a lower productivity index was considered. The production and reinjection parameters given in Table 5-10 for 3D-Model 2 are used in the new model (named 3D-Model 3), but for both the production and reinjection wells the productivity/injectivity index was decreased from 1.09E-09m$^3$ to 1.09E-11m$^3$. The model was run for the various reinjection scenarios considered for 3D-Model 2 (given in Table 5-11).

Figure 5-61 compares the steam production rates for the high (1.09E-09m$^3$) and low (1.09E-11m$^3$) productivity indices. For the low productivity index case the steam production rate starts to decrease much earlier than for the high productivity index case. This result is expected as with a lower productivity index the production rate decreases more quickly as the reservoir pressure declines.

![Figure 5-61 Steam production rates for 3D Model 2 (high productivity index) and 3D-Model 3 (low productivity index) for the no-injection and 15% injection (blue) cases.](image)
Figure 5-62 compares the steam production rate for the no-injection case with that for Scenarios 1, 2 and 3, which have reinjection of 15%, 35% and 50% of produced steam, respectively. According to this figure reinjection at a low level (Scenario 1) into the reservoir increases steam production. However there is no apparent difference between the results with 15%, 35% and 50% reinjection. Figure 5-63a and b shows the total mass production rates and flowing enthalpy histories for the no-injection case and for reinjection of 15%, 35% and 50% of produced steam, respectively. According to this figure increasing the reinjection rate increases the total mass production and decreases the enthalpy of the production fluid. Hence a higher rate of reinjection increases the production of the liquid phase and the amount of produced steam does not change with an increased reinjection rate.

Figure 5-62  Steam production rates for the no-injection case and different reinjection scenarios (3D-Model 3).
Figure 5-63 (a) Total mass production rates (b) flowing enthalpy histories for the no-injection case and different reinjection scenarios (3D-Model 3).

However the scenarios with higher levels of reinjection (Scenarios 5 and 6) show a decreased steam production (see Figure 5-64).
Figure 5-64  Steam production rates for the no-injection case and different reinjection scenarios (3D-Model 3).

Figure 5-65 shows the comparisons of results for the no injection case with those for Scenarios 3 and 4 for 3D-Model 3 (productivity index 1.09E-11m$^3$). For this case, reinjection further from the production zone decreases steam production. Reinjection right above the production wells (Scenario 3), causes the vapour saturation to be higher and the reservoir pressure to be lower than for reinjection further away as in Scenario 4 (Figure 5-66, Figure 5-67).
Figure 5-65  Steam production rates for the no-injection case, Scenario 3 and Scenario 4.
Figure 5-66  Vapour saturation distributions after 100 years of production for: (a) Scenario 3 and (b) Scenario 4.
Figure 5-67  Pressure distributions after 100 years of production for: (a) Scenario 3 and (b) Scenario 4.
Results of experiments on 3D-Model 3 (lower productivity index) show that reinjection at a low level (15%) into the reservoir increases steam production, but increasing the reinjection rate up to 50% does not improve the beneficial effect of reinjection. For higher levels of reinjection (70% or 100%) steam production decreases. For wells with a low productivity index, reinjection right above the production zones gives a higher steam production rate than injecting further away from the production zones.

5.3.4.4 Deeper production zones

One of the most significant reservoir processes that occurs during reinjection is the gravity driven downward migration of reinjected water. Therefore the vertical distance between the reinjection zone and the production zone is an important parameter to consider while planning the reinjection strategy. Thus in this section the case of a deeper production zone was considered. To simulate reinjection effects on steam production for the case of deeper production zones, 3D-Model 2 is taken as the base model. The new model with deep production zones is called 3D-Model 4a.

The locations of the feed zones for this case are shown with red in Figure 5-68. Comparing this figure with Figure 5-50, it can be seen that the upper and lower production layers have been moved 200m and 400m deeper, respectively.
The parameters given in Table 5-10 were used for the spring, production and reinjection wells, except for the cut-off pressures for the production wells. Since the level of production zones has changed, the cut-off pressures of the production wells were adjusted. The pressure value at +500m depth was taken as 15bar and by using the pressure gradient of 1/362.6bar/m the cut-off pressure values at the new production layers were calculated as 15.41, 15.69, 17.21 and 17.76bar (as shown in Figure 5-68).

Figure 5-69 compares the steam production rates for the cases of producing from upper production layers (3D-Model 2) and lower production layers (3D-Model 4a) for no-injection and for 15% reinjection (Scenario 1). This figure shows that producing from deeper layers extends the reservoir life by about 15 years.
Various reinjection scenarios were applied to the 3D-Model 4a with the new deeper production zones to analyse the effect of different reinjection rates on steam production. Comparisons of steam production rates for the no-injection case with five scenarios for reinjection (see Table 5-11) are shown in Figure 5-70 and Figure 5-71. Comparing these two figures with Figure 5-57 and Figure 5-58 shows that the qualitative effect of reinjection on steam production is similar for shallow or deep production. Figure 5-70 shows that for up to 50% reinjection a higher reinjection rate results in a higher production of steam.
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Figure 5-70  Steam production rates for 3D- Model 4a for the no-injection case and different reinjection scenarios.

For a higher reinjection rate (Scenarios 5 and 6) the beneficial effect of reinjection decreases gradually (see Figure 5-71). The difference between the cases of shallow and deep production is that reinjection improves steam production strongly for deep production. Even the highest rate of reinjection supports steam production remarkably well for very long period of exploitation. The reason for this behaviour is the longer vertical distance between injection and production wells that allows further boiling in the injection plume and causes an increase in vapour saturation and reservoir pressure. This prevents the breakthrough of injected water. Therefore a large vertical distance between production and injection wells prevents detrimental cooling effects caused by the reinjection fluid returning prematurely to the production wells.
Real field experiences also show that, injection has had an important role in maintaining steam production in two-phase vapour-dominated reservoirs (Darajat, Kamojang, Larderello, Pohiphi, see Kaya et al. (2009)). In The Geysers, the depths of the production and reinjection wells are inter-mixed (Enedy et al. (1993)). The production wells that are close to reinjection wells are affected by the breakthrough of the injected fluid (Goyal (1998)). Excessive infield reinjection caused the collapse of the steam saturation and sudden loss of productivity from some wells (Sanyal et al. (1995)). Additionally the wells that reinjected at high rates for a prolonged period of time also caused declines in the steam flowrate (Enedy et al. (1993)). The overall effect of infield reinjection was beneficial for The Geysers, and therefore, in addition to reinjection of condensate, injection of secondary treated waste water has been started to increase steam production. (Stark et al. (2005)).

In Larderello field, production started in 1913 (Cappetti and Lio Ceppatelli (2005)). Reinjection started in the early 1970s (Cappetti et al. (1995)) and from 1983 all the steam condensate was reinjected in the shallow reservoir. Within fifteen years...

Figure 5-71 Steam production rates for 3D-Model 4a for the no-injection case and different reinjection scenarios.
shallow infield reinjection resulted in an increase in reservoir pressure and stabilization of the temperature (Cappetti and Stefani (1994)).

5.3.4.5 Deeper production zones and lower productivity indices

As in Section 5.3.4.3, the case of a low productivity index (1.09E-11 m³) for the production wells was also examined for 3D-Model 4a (the case with deeper production zones). This new model is named 3D-Model 4b. Results for various reinjection scenarios (Table 5-11) are shown in Figure 5-72 and Figure 5-73. Comparison of Figure 5-62 and Figure 5-64 with Figure 5-72 and Figure 5-73 shows that when the production zones are located deeper, the qualitative effect of reinjection is similar. As for 3D-Model 3, if productivity index is lower, there is not much difference on the beneficial effect of reinjection for the reinjection cases between 15% and 50%. At higher levels of reinjection (70% or 100%) steam production decreases. The only difference from 3D-Model 3 is that the effect of reinjection is more significant for the model that has deeper production zones (3D-Model 4b).

![Figure 5-72 Steam production rates for 3D-Model 4b for the no-injection case and different reinjection scenarios.](image)
5.3.4.6 Lower flow rates for the production wells

Up until this stage, all the 3D models have used four production wells, each well producing a maximum steam rate of 64kg/s. The well productivity may not be this high in some geothermal fields because of permeability and feed zone restrictions. Therefore in this section a lower production rate from each well is considered. This allows us to analyse whether or not distributing the production more widely over the field by increasing number of wells will be beneficial to steam production and whether it will change the effect of reinjection.

3D-Model 4a was chosen as the base model, and therefore the case of deeper production layers (see Figure 5-68) was considered and the productivity index for the production wells was kept at 1.09E-9m³. The new Model is called 3D-Model 5. The number of production wells was increased to fifteen and to keep the total maximum flow rate constant, maximum steam production rate for each well was

Figure 5-73 Steam production rates for 3D-Model 4b for the no-injection case and different reinjection scenarios.
decreased to 17.07kg/s. Since each well produces from eight blocks, the maximum steam flow assigned to each grid-block was 2.13kg/s.

Figure 5-74 shows the areal location of the production and injection wells. In the figure, the red blocks are the production blocks.

Three cases of reinjection were considered.

**Case A- Intermediate reinjection above the production wells:** In this case 50% of the produced steam is injected above the production wells into the red grid blocks (see Figure 5-74). The areal locations of the production and injection wells are the same. The vertical locations of production and injection wells are as shown in Figure 5-68.

**Case B- High reinjection above the production wells:** In this case 100% of the produced steam is injected above the production wells into the red and blue grid blocks (see Figure 5-74). The vertical locations of production and injection wells are same as for Case A.

**Case C- Intermediate reinjection, further away from the production wells:** In this case 50% of the produced steam is injected into the yellow grid blocks that are 150-500m from the production wells. The aim of this case is to see the effect of the areal location of the injection wells. The vertical locations of the production and injection wells are same as for Case A.
Figure 5-74  Locations of the production wells (red grid-blocks) and locations of the injection wells (Case A-red, Case B-red and blue, Case C yellow) for 3D-Model 5.

Figure 5-75 shows the effect of increasing the number of production and injection wells. The figure also compares the steam production rates for the no-injection case with Case A (50% reinjection) and Case B (100% reinjection). According to Figure 5-75, if production from a vapour-dominated geothermal field is scattered through the field with an increased number of production wells, production from the field increases considerably in the long term. A medium rate of reinjection (Case A) extends the reservoir life about 20 years, while this support is only about 12 years for 3D Model 4a with four production wells. The high amount of support from reinjection continues after steam production starts to drop from its maximum value. A very high rate of reinjection (Case B) also extends the reservoir life and
increases steam production. But after about 85 years of production, Case B starts to produce a smaller amount of steam than the no-injection case.

Figure 5-75  Steam production rates for the no-injection case and two different rates of reinjection for 3D-Model 4a (four production wells) and 3D-Model 5 (fifteen production wells).

The effect of the location of reinjection wells was analysed by comparing results for Case A and Case C. Figure 5-76 shows this comparison. According to the figure there is no significant difference whether the injection is applied right above the production wells or in blocks that are located at the top of the reservoir but areally 150-500m away from production wells.
Figure 5-76 Steam production rates for 3D-Model 5 for the no-injection case and the 50\% reinjection case, for Case A (reinjection directly above production) and Case C (reinjection distributed).

5.3.5 Summary

Section 5.3 describes modifications of the 3D Darajat model that were made based on the experiences we obtained from the 2D modelling study (Section 5.2). In addition to these modifications a horizontally and vertically finer grid structure was adopted for the production and injection zones (3D-Model 2). To investigate the effect of reinjection on steam production various production schemes and reinjection strategies were tested with two different productivity index values. Results of these investigations show that;

1- Reinjecting up to 50\% of the produced steam always increases steam production significantly. However for higher reinjection rates, the discharge enthalpy may reduce and the steam production rate may decline owing to the breakthrough of cold reinjection fluid.
2- If the reservoir is producing with a high productivity index, increasing reinjection rate from 15% to 50% increases the steam production rate gradually. However if the productivity index is low, increasing the reinjection rate from 15% up to 50% does not effect the steam production rate.

3- For the case of a high productivity index, if the areal location of the production wells is further from the injection wells then reinjection is more beneficial. However for a low productivity index, injecting right above the production zones gives a higher steam production rate.

4- Cold reinjection water will migrate to deeper zones under the effect of gravity. If the feed zones of the production wells are deeper, the reinjection fluid will have a longer time to heat up, boil and support the reservoir pressure. Therefore the effect of reinjection is much more beneficial if the production zones are deeper.

5- If production is from a large number of wells that are scattered throughout the field, then the steam production rate does not drop as quickly. A medium rate of reinjection (50%) extends the reservoir life and provides a high steam production rate for a long time. A very high rate of reinjection also increases the steam production rate but in the long term shows detrimental cooling affects and decreases steam production.
Chapter 6. Summary, Conclusions and Future Work

6.1 Summary and conclusions

The aim of this thesis was to use computer modelling of reinjection into geothermal reservoirs to decide upon optimum reinjection strategies.

The literature survey of worldwide reinjection presented in Chapter 1 indicates that the effect of injection on production depends on whether the geothermal system is vapour-dominated, liquid-dominated or hot water. According to this review:

Infield reinjection had very few adverse effects on the thermodynamic state of the reservoirs for two-phase, vapour-dominated reservoirs and overall it has assisted steam production (e.g. Darajat, Kamojang, Larderello, Poihipi).

In two-phase, liquid-dominated reservoirs often thermal breakthrough is observed when infield reinjection is carried out. In most cases the adverse effects of reinjection have been reversed when the infield reinjection was abandoned or reduced (e.g. Tiwi, Ahuachapan, Miravalles, Hatchobaru, Uenotai, Bulalo, Tongonan, Palipinon, Onikobe, Mindanao, Olkaria I). However, in a few cases long term adverse effects can be seen after the reinjection was moved outfield (e.g. Mori).

Thermal breakthrough has been experienced in most hot-water reservoirs as well (e.g. Pauzhetsky, Kizildere, East Mesa, Beowawe, Brady, Empire, Steamboat). But infield reinjection has helped with pressure maintenance (e.g. Pauzhetsky, Kizildere). In some cases moving reinjection wells closer to production wells has had a positive effect by reducing drawdown (e.g. Beowawe).
In Chapter 2 reinjection effects in two-phase reservoirs were tested by using a hypothetical model. The simple 3D closed box model used by Sigurdsson et al. (1995) and Sigurdsson and Stefansson (1998) was chosen as a reference case. For this study the Sigurdsson model was extended to investigate the effect of the natural recharge from shallow groundwater, from the basement of the system and laterally from the boundaries of the system. According to results of numerical experiments with this model, the effects of injection into a two-phase liquid-dominated geothermal reservoir strongly depend on the recharge conditions. Injection may increase steam flow if recharge is very small and the reservoir is acting as a closed system, or if the caprock is permeable and production induces cold groundwater recharge. But otherwise injection may decrease steam flow from production wells by suppressing hot recharge from depth or replacing lateral recharge by colder injected water.

The review of past experience of reinjection practices presented in Chapter 1 indicates that the effect of reinjection on production performance depends on the structure of the individual system. However there are some generic similarities depending on whether the system is hot-water, liquid-dominated or vapour-dominated. Therefore in Chapter 3, Chapter 4 and Chapter 5 we investigated the effect of reinjection in these three types of geothermal reservoirs.

For the case of reinjection into hot-water reservoirs there is a fundamental tension between the beneficial pressure maintenance effect of reinjection and the negative effect of the thermal breakthrough of cold reinjected water. Therefore the aim of Chapter 3 was to decide which strategy is the best for keeping the reservoir pressure and total discharge high, without reducing the discharge enthalpy by thermal breakthrough or cold water recharge induced by the pressure drop. A 3D numerical model of the East Mesa field was chosen as a generic model. Then a laterally closed version (no-lateral recharge) and a laterally open version (mass is allowed to flow across the side boundaries) of this model were examined for close-infield, far-infield and outfield reinjection scenarios, using various reinjection depths. An evaluation of all the reinjection scenarios shows that far-infield reinjection supports the reservoir pressure adequately without causing an early breakthrough of reinjected fluid. Reinjection into deep zones maintains the
reservoir pressure and prevents cold natural recharge, thus decreasing the risk of thermal breakthrough and increasing the production enthalpy and power output. Therefore reinjection applied far-infield and deep provides the optimum strategy for hot-water systems.

A 3D numerical model of the Wairakei-Tauhara field was chosen as a representative model to investigate the effect of reinjection on liquid dominated two-phase systems (Chapter 4). The impacts of different rates of outfield and infield reinjection on production enthalpy, reservoir pressure and temperature, recharge conditions and surface features were investigated. According to the results presented in this chapter, since 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. Because the quantity of hot water to be disposed of is large in this type of reservoir, outfield reinjection should be preferred for the disposal of all or part of the separated geothermal fluid.

Infield reinjection prevents a large pressure drop in liquid-dominated two-phase systems. However a large drop in the reservoir pressure causes boiling in the reservoir and hence results in the formation of zones with high vapour saturation. Production of a high enthalpy mixture of water and steam is an advantage because the conversion of thermal energy to electricity is more efficient and less separated geothermal water has to be dealt with. Infield reinjection prevents the increase in the steam fraction and causes a drop in the production enthalpies. Additionally a large pressure drop induces strong hot water recharge from the base and side boundaries of the system. When pressure is maintained by cold reinjection, natural recharge of hot water to the system is suppressed.

Modelling results discussed in Chapter 4 also show that 100% infield reinjection may cause significant cooling in the production zones. A decrease in the reinjection rate down to 50% of the separated geothermal water results in a smaller decline in the production enthalpy but still causes a loss of energy production capacity. A still lower rate of reinjection (25% of separated geothermal water) does not cause a significant pressure decline or significant cooling. Therefore this scenario provides a good reinjection strategy.
According to Chapter 4, infield reinjection has a strong effect on the surface manifestations. If the reinjection zone is close to the surface features a significant decline or disappearance of surface features occurs. However, if there is less hydraulic communication between production and reinjection areas, then reinjection may prevent the decline in the surface manifestations without showing a cooling effect. If production is carried out without reinjection, there is a significant pressure drawdown, the flow of chloride water from the deep aquifers to the surface features decreases with time and the ground surface tends to become steam heated. Reinjection supports the flow of chloride water to the surface features, but at a lower temperature than that of the discharge in the natural state.

A study of injection in vapour-dominated system was discussed in Chapter 5. The Darajat geothermal field was used as a representative system. First numerical experiments were carried out using a 2D model in order to obtain a model which exhibits representative behaviour of vapour-dominated reservoirs, such as Larderello or The Geysers, where infield reinjection has had an important role in maintaining steam production. Model parameters such as vertical permeability, porosity and relative permeability were investigated and different reinjection rates and start-times for reinjection were tried. Various aspects of model design such as grid refinement, use of an embedded radial grid near the wells, dual porosity and nine-point differencing were investigated.

Based on the experiences obtained from the investigations of a 2D model, the existing 3D Darajat model was modified. The modified 3D model was used to test the effect of reinjection on steam production by using various production schemes and reinjection strategies. Results of these investigations show that:

i) Reinjection of up to 50% of the produced steam always increases steam production. However for higher reinjection rates, the discharge enthalpy reduces and steam production declines because of the breakthrough of cold reinjected fluid.

ii) If the vertical distance between production and reinjection zones is large the reinjection fluid will have a longer time to heat up and boil, and hence
support the reservoir pressure. In this case the beneficial effect of reinjection is much more significant.

iii) If the field is producing from a larger number of wells that are scattered through the field, steam production does not drop as quickly. A medium rate of reinjection (50%) provides a high amount steam production over the long term. A very high rate of reinjection also increases steam production but in the long term shows detrimental cooling affects and decreases steam production.

iv) If the wells have a high productivity index then reinjection further away horizontally, instead of right above the production wells, is more beneficial. However for the low productivity index case, reinjection right above the production zones gives the highest steam production rate.

6.2 Future work

Several areas of research discussed in this thesis could be extended by further work, including:

1- Sigurdsson model used 3 different patterns for the location of production and reinjection: an intermixed pattern, a peripheral pattern and a dipole pattern. For the investigations discussed in Chapter 2 we only tested the impacts of reinjection for the dipole pattern. This study could be extended to investigate the effect of reinjection for the peripheral and dipole configurations as well.

2- For the research presented in this thesis we did not consider water-rock interactions. However the majority of the reinjection waters are high saline brines. Reinjection of such brines into a reservoir may lead to a change of the permeability and porosity of the formation rock due to mineral dissolution or precipitation. These changes in the rock properties affect the fluid flow and the injectivity of the wells. Xu et al. (2008) have developed a non-isothermal reactive geochemical transport code (TOUGHREACT) which includes a comprehensive capability for
modelling chemical reactions between the liquid, gaseous and solid phases coupled with solute transport and sub-surface multiphase fluid and heat flow. Therefore the 2D and 3D models that we used for this thesis (for Chapter 2, Chapter 3, Chapter 4 and Chapter 5) could be modified to include the effects of precipitation and dissolution on rock porosity and permeability and hence their effect on reinjection and production performance.

3- During cold water injection into geothermal reservoirs, the pore pressure increases. The induced stress changes may cause formation fracturing and the fracturing may cause early cold water breakthrough into production wells. In naturally fractured, stress sensitive reservoirs changes in the state of stress cause opening or closing of existing fractures and therefore a change in permeability. In the further studies, the inclusion of reservoir stresses may give more accurate models of reinjection.

4- For the experiments on the 2D model of a vapour-dominated reservoir (Chapter 5 Section 5.2) we mainly used a porous medium model. For one case (Model 11a and Model 11b) we tried a fractured medium with a regular structure. However Pruess (1996) shows that while injection into homogeneous media produces compact smooth-shaped plumes, heterogeneous fractures give rise to complex fingering flows with dendritic patterns. He generated stochastic permeability distributions, based on the essential characteristics of fractures in hard rock of very low permeability. His study indicated that in heterogeneous fractures there is a much stronger lateral flow, suggesting that there may be more potential for water interference at neighbouring production wells than would be predicted by homogeneous fracture (or porous medium) models. Therefore a further model could be set up to investigate the effect of reinjection on production in a model with heterogeneous fractures.

5- Pruess (1994a) and Pruess (1995) investigated the effect of phase dispersion on the behaviour of an injection plume by applying a Fickian type dispersive term for phase dispersion. These studies showed that phase dispersion enhances the lateral movement and diminishes the downward movement of the plume of reinjected water and neglecting this process may lead to an underestimate of the potential for...
cold water breakthrough. Therefore for the experiments on the 2D model of vapour dominated reservoir (Chapter 5 Section 5.2) a further model could be set up to investigate the effect of phase dispersion on the impacts of reinjection.

6- Oldenburg and Pruess (2000) and Croucher et al. (2004) indicate that reinjection simulations with standard finite-difference techniques can lead to problems with numerical dispersion and may erroneously predict the early breakthrough of a tracer since numerical dispersion has the effect of smoothing out sharp fronts in scalar quantities (e.g. temperature, liquid saturation, tracer concentration) transported by the flow. To obtain an accurate numerical solution for strong advective flows of multiphase non-isothermal flows, Oldenburg and Pruess (2000) implemented the Leonard total variation diminishing (LTVD) schemes into the implicit geothermal reservoir simulator TOUGH2. And Croucher et al. (2004) developed a simulator which uses Eulerian–Lagrangian methods (ELMs) in conjunction with flow fields generated by TOUGH2. One of these methods could be included in the numerical experiments with the 2D model of a vapour-dominated reservoir (Chapter 5 Section 5.2).
Appendix
<table>
<thead>
<tr>
<th>Country</th>
<th>Field</th>
<th>Start Date</th>
<th>Current Generation, MWe</th>
<th>Total Mass Produced, t/h</th>
<th>Average Enthalpy, kJ/kg</th>
<th>Reinjection Rate, t/h</th>
<th>Reinjection Strategy</th>
<th>Effects of Reinjection</th>
<th>References</th>
<th>Additional Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>Langju (Tibet)</td>
<td>1987</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Zheng et al. (2005)</td>
<td>Fluid temperature 80-180°C</td>
</tr>
<tr>
<td></td>
<td>Nagqu (Tibet)</td>
<td>1993</td>
<td>1</td>
<td>300</td>
<td>470</td>
<td>0</td>
<td>Surface discharge</td>
<td>n/a</td>
<td>Low and Morris (2000); Zheng et al. (2005)</td>
<td>Fluid temperature 110-114°C</td>
</tr>
<tr>
<td></td>
<td>Yangbajain (Tibet)</td>
<td>1977</td>
<td>24.18</td>
<td>650</td>
<td>~70%</td>
<td>Initially discharged to Zangbu River, in 2002 around 70% infield reinjection into shallow reservoir</td>
<td></td>
<td>Cappetti and Fangzhi (1985); Hutter (2001); Xiaoping (2002); Zheng et al. (2005)</td>
<td>Xiaoping (2002) output capacity 45.43 MWe and 917.2 kg/s for 31 wells.</td>
<td></td>
</tr>
<tr>
<td>Iceland</td>
<td>Husavik</td>
<td>2000</td>
<td>2</td>
<td>324</td>
<td>0</td>
<td>Surface discharge</td>
<td>n/a</td>
<td>Johnson and Mlck (2002); Mlck et al. (2002); Ragnarsson (2005); SKM (2004)</td>
<td>Fluid temperature 121°C. Heat is also used for district heating</td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>Ogiri</td>
<td>1996</td>
<td>30</td>
<td>1250</td>
<td>975</td>
<td>Total reinjection</td>
<td></td>
<td>Horikoshi et al. (1998); Kawazoe and Shirakura (2005)</td>
<td>Production and reinjection rates are based on 1998 data</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Takigami</td>
<td>1996</td>
<td>25</td>
<td>1270</td>
<td>925</td>
<td>1100</td>
<td>Total outfield injection</td>
<td></td>
<td>Fujimitsu et al. (2000); Furuya et al. (2000); Goto (2000); Kawazoe and Shirakura (2005)</td>
<td></td>
</tr>
<tr>
<td>Country</td>
<td>Field</td>
<td>Start Date</td>
<td>Current, Generation, Mwe</td>
<td>Total Mass Produced, t/h</td>
<td>Average Enthalpy, kJ/kg</td>
<td>Reinjection Rate, t/h</td>
<td>Reinjection Strategy</td>
<td>Effects of Reinjection</td>
<td>References</td>
<td>Additional Notes</td>
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</tr>
<tr>
<td>Russia</td>
<td>Pauzhetsky, Kamchatka</td>
<td>1967</td>
<td>11</td>
<td>864</td>
<td>780</td>
<td>140</td>
<td>Partial infield/edge-field reinjection. Reinjection started in 1979, no reinjection between 1988-1993.</td>
<td>Re injection started to compensate for the loss of mass and to maintain pressure. At the earlier time of production the enthalpy is about 800kJ/kg but some production wells near to reinjection decreased by 100-150 kJ/kg.</td>
<td>Kiryukhin and Yampolsky (2004); Kononov and Povarov (2005)</td>
<td>A high production rate caused large changes in enthalpy. As the result of a significant enthalpy drop the northern section of the field was abandoned in 1997. The central section of the field has also suffered a temperature decline.</td>
</tr>
<tr>
<td>Thailand</td>
<td>Fang</td>
<td>1989</td>
<td>0.18</td>
<td>60</td>
<td>0</td>
<td>Likely to be surface discharge</td>
<td></td>
<td></td>
<td></td>
<td>Huttner (2001)</td>
</tr>
<tr>
<td>Turkey</td>
<td>Kizildere</td>
<td>1984</td>
<td>10</td>
<td>1000</td>
<td>875</td>
<td>225</td>
<td>Partial (20%) infield reinjection to the shallow reservoir started in 2002. Remaining brine (80%) is discharged into river.</td>
<td>After 17 months of reinjection cooling was observed at the nearest well and this well has ceased production. The allowable production rate was increased from 830t/h to 1000t/h.</td>
<td>Satman et al. (2005); Serpen (2007); Şimşek et al. (2005); Yeltekin and Parlaktuna (2006)</td>
<td>A modelling study investigating the effect of reinjection recommended that the shallow reservoir should be used for reinjection.</td>
</tr>
<tr>
<td>Turkey</td>
<td>Salavatli</td>
<td>2006</td>
<td>6.5</td>
<td>545</td>
<td>710</td>
<td>450</td>
<td>Infield reinjection (about 1.1 and 2.5 km away from production wells)</td>
<td>Not available</td>
<td>Serpen (2007)</td>
<td>Two production and one reinjection wells are being planned for a 10MWe power plant</td>
</tr>
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<td>Country</td>
<td>Field</td>
<td>Start Date</td>
<td>Current Generation, Mwe</td>
<td>Total Mass Produced, t/h</td>
<td>Average Enthalpy, kJ/kg</td>
<td>Reinjection Rate, t/h</td>
<td>Reinjection Strategy</td>
<td>Effects of Reinjection</td>
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<td>Additional Notes</td>
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<tr>
<td>USA</td>
<td>Beowawe</td>
<td>1985</td>
<td>16.6</td>
<td>928.3</td>
<td>8</td>
<td>760*</td>
<td>Initially outfield reinjection, reinjection moved in 1994 closer to the production wells.</td>
<td>Temperature decline from recharge and reinjection returns. Moving reinjection towards production wells had a positive impact by reducing drawdown.</td>
<td>Benoit and Stock (1993); Bertani (2005); Butler et al. (2001); Lund et al. (2005)</td>
<td>Enthalpy declined. *From 920kJ/kg (in 1986) to 760kJ/kg (in 2000)</td>
</tr>
<tr>
<td>USA</td>
<td>Brady</td>
<td>1992</td>
<td>8.8</td>
<td>1772</td>
<td></td>
<td></td>
<td>Initially infield reinjection, 60% of injection fluid moved outfield by 2001.</td>
<td>Reinjection returned during infield reinjection (temperature declined and tracer returns observed)</td>
<td>Ettinger and Brugman (1992); Kaplan and Schochet (2005); Krieger and Sponsler (2002); Lund et al. (2005)</td>
<td>Temperature of produced fluid was 182°C in 1992, Initially temperatures in the production wells declined rapidly reaching 162°C by mid-1993. By mid-1995 the temperature was 158°C and trending downward.</td>
</tr>
<tr>
<td>USA</td>
<td>Casa Diablo</td>
<td>1985</td>
<td>40</td>
<td>2794</td>
<td></td>
<td>2645</td>
<td>Infield reinjection</td>
<td>A temperature decline was observed. A shift to deeper injection decreased the temperature decline but increased the pressure decline.</td>
<td>Bergfeld et al. (2006); Bertani (2005); California Department of Conservation (2004); Howle et al. (2003); SKM (2004); Sorey and Farrar (1998)</td>
<td>Reservoir temperature is 150-175°C</td>
</tr>
<tr>
<td>Country</td>
<td>Field</td>
<td>Start Date</td>
<td>Current, Generation, Mwe</td>
<td>Total Mass Produced, t/h</td>
<td>Average Enthalpy, kJ/kg</td>
<td>Reinjection Rate, t/h</td>
<td>Reinjection Strategy</td>
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<tr>
<td>USA</td>
<td>Coso</td>
<td>1987</td>
<td>274</td>
<td>4028</td>
<td>840-2800</td>
<td>1814</td>
<td>Infield reinjection of fluid and gas</td>
<td>Gas breakthrough due to reinjection of gas required additional H2S abatement systems</td>
<td>California Department of Conservation (2004); Environment Hawaii (1992); Hirtz et al. (1993); Lund et al. (2005); McLin et al. (2006); Schoonmaker and Maricle (1990)</td>
<td>For Ormesa power plants 100% of all produced fluid and gas are injected. Reservoir temperature range from 146 to 182°C.</td>
</tr>
<tr>
<td>USA</td>
<td>East Mesa</td>
<td>1979</td>
<td>79</td>
<td>8776</td>
<td>8134</td>
<td>Total infield reinjection</td>
<td>Reinjection returns results in cooling of approximately 1°F per year.</td>
<td>Bertani (2005); California Department of Conservation (2004); Massonnet et al. (1997); Schochet et al. (2004); Sonnellitter et al. (2000)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>Empire</td>
<td>1987</td>
<td>4.8</td>
<td></td>
<td></td>
<td>Edgefield reinjection</td>
<td>Initially the temperature decline due to injection. Then a program of partial surface discharge was instituted to create a wildlife wetland.</td>
<td>Bloomquist (2004); Lund et al. (2005); Schochet (2000)</td>
<td></td>
<td>The fluid temperature was 137°C, falling to as low as 114°C by 1996. The dehydration plant is supplied with 168-252 t/h of geothermal fluid at a minimum temperature of 141°C.</td>
</tr>
<tr>
<td>Country</td>
<td>Field</td>
<td>Start Date</td>
<td>Current, MWe</td>
<td>Total Mass, t/h</td>
<td>Average Enthalpy, kJ/kg</td>
<td>Reinjection Rate, t/h</td>
<td>Reinjection Strategy</td>
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<td>Additional Notes</td>
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<tr>
<td>USA</td>
<td>Heber</td>
<td>1985</td>
<td>85</td>
<td>7044</td>
<td>1010</td>
<td>6877</td>
<td>Total infield / edge-field reinjection</td>
<td></td>
<td>California Department of Conservation (2004); Hirtz and Lovekin (1995); Lund et al. (2005); Sanyal et al. (1995); Sones and Krieger (2000); Stefansson (1997)</td>
<td>Based on 47 MWe unit reinjection caused ground inflation</td>
</tr>
<tr>
<td>USA</td>
<td>Puna (Hawaii)</td>
<td>1984</td>
<td>30</td>
<td>907</td>
<td>Total infield injection</td>
<td>No reinjection returns</td>
<td></td>
<td></td>
<td>Environment Hawaii (1992); Gill (2004); Lund et al. (2005); Puna Geothermal Venture Hawaii</td>
<td>In 1989, 3.6 MWe binary plant uses about 182 t/h at 182 °C, with total reinjection of waste fluid.</td>
</tr>
<tr>
<td>USA</td>
<td>Soda Lake</td>
<td>1987</td>
<td>26.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lund et al. (2005); Ram and Krieger (1989)</td>
<td>Reservoir temperature is 160°C. Physical constraints prevent the relocation of reinjection wells away from the production wells.</td>
</tr>
<tr>
<td>USA</td>
<td>Steamboat Springs</td>
<td>1986</td>
<td>31</td>
<td>1370</td>
<td>Total infield reinjection. Production and injection use the same shallow aquifer.</td>
<td>Tracer tests show that most of the injected water remains within the well field. An average temperature decline of 1°C per year has been measured.</td>
<td></td>
<td></td>
<td>Bertani (2005); Lund et al. (2005); Rose et al. (1999); SKM (2004); Sorey (2000)</td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>Steamboat Hills</td>
<td>1988</td>
<td>14.4</td>
<td>85-95% of prod. rate</td>
<td>85-90% infield reinjection</td>
<td>Reinjection water is mixed with the municipal domestic water.</td>
<td></td>
<td></td>
<td>Lund et al. (2005); Skalbeck et al. (2002); Sorey (2000)</td>
<td>Reservoir temperature is 170-220°C.</td>
</tr>
<tr>
<td>USA</td>
<td>Stillwater</td>
<td>1989</td>
<td>21</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lund et al. (2005)</td>
<td></td>
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369
<table>
<thead>
<tr>
<th>Country</th>
<th>Field</th>
<th>Start Date</th>
<th>Current Generation, Mwe</th>
<th>Total Mass Produced, t/h</th>
<th>Average Enthalpy, kJ/kg</th>
<th>Reinjection Rate, t/h</th>
<th>Reinjection Strategy</th>
<th>Effects of Reinjection</th>
<th>References</th>
<th>Additional Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costa Rica</td>
<td>Miravalles</td>
<td>1994</td>
<td>162.5</td>
<td>5556</td>
<td>1100</td>
<td>4700</td>
<td>1994-1998 infield injection from west and edgefield from south. 1998-2000 reinjection from west decreased and south increased. 2000-2002 injection directed to the south. In late 2002 a portion of the water injected in the south was diverted back to the western sector of the field to mitigate the pressure drop.</td>
<td>1994-1997 reinjection return observed with chemical breakthrough but no noticeable thermal breakthrough. 1999-2002 Thermal breakthrough occurred towards the east with the effect of injection coming from the south. Chemical breakthrough was noticed in the central wells too. Relocating the reinjection wells back to western part has been noticed chemically.</td>
<td>Gonzalez-Vargas et al. (2005); Mainieri (2005); Moya and Yock (2000); Moya and Yock (2005)</td>
<td></td>
</tr>
<tr>
<td>El Salvador</td>
<td>Ahuachapan</td>
<td>1975</td>
<td>60-65</td>
<td>2818.8</td>
<td>1100</td>
<td>1656</td>
<td>From 1976 until November 1982 an average 25-30% of the extracted fluid was injected infield. Surface discharge + partial outfield reinjection 1982-2004. Total outfield reinjection from 2004.</td>
<td>Infield reinjection caused thermal breakthrough. Wells recovered when infield reinjection was stopped. Outfield reinjection (&gt; 4km from production area) required pumps</td>
<td>Horne (1982); Perez Flores and Treviño (1997); Quijano (2000); Quijano et al. (2001); Steingrimsson et al. (1991); Umanzor (2005)</td>
<td>Total mass production capacity is 2818.8 t/h Quijano (2000) for 55 MWe</td>
</tr>
<tr>
<td>France</td>
<td>Bouillante, Guadeloupe</td>
<td>1987</td>
<td>14.7</td>
<td>N/A</td>
<td>Surface discharge</td>
<td>N/A</td>
<td>Huttner (2001); Laplaige et al. (2005)</td>
<td>Reservoir temperature is 250°C.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Country</td>
<td>Field</td>
<td>Start Date</td>
<td>Current Generation, Mwe</td>
<td>Total Mass Produced, t/h</td>
<td>Average Enthalpy, kJ/kg</td>
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<td>Reinjection Strategy</td>
<td>Effects of Reinjection</td>
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<td>Additional Notes</td>
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</tr>
<tr>
<td>Japan</td>
<td>Mori</td>
<td>1982</td>
<td>22.5</td>
<td>2050</td>
<td>1200</td>
<td>Total Infield reinjection from 1982-1985. From 1986, 500/t/h of the reinjection fluid moved further out from production wells, and deeper production wells have introduced. From 1991 production was decentralized, production and reinjection zones were relocated giving much larger separation. Currently the waste fluids are injected infield and outfield.</td>
<td>Reinjection returns appeared after one year from the start of the production. Changes in the production injection scheme from 1986 has reduced the returns but accelerated pressure decline, which caused the inflow of shallow ground water and decreased the enthalpy of produced fluid. Due to the enthalpy decline, 3 wells stopped production in 1987-1988. Modifications from 1991, led to gradual recover of the production but still there is a reinjection return.</td>
<td>Hanano et al. (2005); Kawazoe and Shirakura (2005)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>Onikobe</td>
<td>1975</td>
<td>12.5</td>
<td>241</td>
<td>980</td>
<td>150</td>
<td>Total infield reinjection. New reinjection techniques have been applied for acidic and neutral fluids.*</td>
<td>Enthalpy decline between 1975-1985 because of reservoir temperature decline caused by local reinjection. Changing production reinjection scheme has stopped enthalpy decline.</td>
<td>Akasaka et al. (2001); Kawazoe and Shirakura (2005); Nakanishi and Iwai (2000); SKM (2004)</td>
<td>&quot;Separated liquids from acidic wells are expanded to atmosphere and then injected. Separated neutral fluids are maintained at high pressure and reinjected under positive wellhead pressure, to maintain temperature and keep the silica in solution.&quot;</td>
</tr>
</tbody>
</table>

*Separated liquids from acidic wells are expanded to atmosphere and then injected. Separated neutral fluids are maintained at high pressure and reinjected under positive wellhead pressure, to maintain temperature and keep the silica in solution.
<p>| Country     | Field               | Start Date | Current Generation, Mw | Total Mass Produced, t/h | Average Enthalpy, kJ/kg | Reinjection Rate, t/h | Reinjection Strategy                                                                 | Effects of Reinjection                                                                 | References                                                                                   | Additional Notes                                                                                     |
|-------------|---------------------|------------|------------------------|-------------------------|-------------------------|-----------------------|-------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|
| New Zealand | Ngawha              | 1997       | 10                     | 416.6                   | 975                     | 391.6                 | Total infield reinjection                                                           | Reinjection returns. No information on thermal breakthrough.                               | Christenson and Scott (2003); Dunstall (2005); Glover and Scott (2005); Kaya (2002); Thain and Dunstall (2000) |
| New Zealand | Wairakei-Tauhara    | 1958       | 190                    | 6250                    | 1050                    | 2500                  | Initially infield, currently partial infield/edge-field reinjection. 2500 t/h is discharged into river. | Reinjection returns observed during tracer tests.                                        | Bixley et al. (1992); Mannington (2007); Mannington et al. (2000); Mannington et al. (2004) |
| Nicaragua   | Momotombo           | 1983       | 77.5                   | 1293                    | 1033                    | 83 % Infield reinjection                                                          |                                                                                       | Mayorga (2005); Rodriguez (1989)                                                            |
| Portugal    | Pico                | 1980       | 10                     | 422                     | 1100                    | N/A                   | Surface discharge                                                                  | N/A                                                                                         | Kaplan (2005); Martins Carvalho et al. (2005)                                              |</p>
<table>
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<th>Country</th>
<th>Field</th>
<th>Start Date</th>
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<th>Total MassProduced t/h</th>
<th>Average Enthalpy, kJ/kg</th>
<th>Reinjection Rate, t/h</th>
<th>Reinjection Strategy</th>
<th>Effects of Reinjection</th>
<th>References</th>
<th>Additional Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>Dixie Valley</td>
<td>1988</td>
<td>62</td>
<td>2600</td>
<td>2100</td>
<td></td>
<td>Reinjection started in 1988. Infield reinjection to the shallower and deeper zones.</td>
<td>Reinjection returns have been recorded but no cooling. Good pressure support from reinjection.</td>
<td>Bertani (2005); Reed (2007); SKM (2004)</td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>Roosevelt Hot Springs (Utah)</td>
<td>1984</td>
<td>26</td>
<td>1043</td>
<td>1065</td>
<td></td>
<td>Infield reinjection</td>
<td></td>
<td>Lund et al. (2005); Yearsley (1994)</td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>Salton Sea</td>
<td>1982</td>
<td>336</td>
<td>14172</td>
<td>1010</td>
<td>11060</td>
<td>Total injection (some injection wells are infield)</td>
<td>unknown</td>
<td>California Department of Conservation (2004); Hirtz and Lovekin (1995); Hulen et al. (2002); Lund et al. (2005)</td>
<td></td>
</tr>
</tbody>
</table>
Table 3 Two-phase, medium enthalpy reservoirs

<table>
<thead>
<tr>
<th>Country</th>
<th>Field</th>
<th>Start Date</th>
<th>Current, Mwe</th>
<th>Total Mass Produced, t/h</th>
<th>Average, kJ/kg</th>
<th>Reinjection Rate, t/h</th>
<th>Reinjection Strategy</th>
<th>Effects of Reinjection</th>
<th>References</th>
<th>Additional Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>El Salvador</td>
<td>Berlin</td>
<td>1992</td>
<td>56</td>
<td>1768</td>
<td>1348</td>
<td>1260</td>
<td>Total Infield reinjection started in 1999. The injection is done in two ways: hot injection into the deep reservoir and shallow aquifer and cold injection into the shallow aquifer.</td>
<td>Reinjection returns indicated by chemicals. No thermal breakthrough.</td>
<td>Bertani (2007); Castro et al. (2006); Montalvo and Axelsson (2000); Monterrosa (2003); Rodriguez (2000); Rodriguez and Herrera (2005)</td>
<td>In 1999 2x5 MWe wellhead unit replaced by a 2x28MWe power plant.</td>
</tr>
<tr>
<td>Guatemala</td>
<td>Amatitlan</td>
<td>1998</td>
<td>5</td>
<td>110</td>
<td>1300</td>
<td></td>
<td>Infield reinjection</td>
<td>unknown</td>
<td>Flores-Armenta et al. (2002); Manzo (2005)</td>
<td></td>
</tr>
<tr>
<td>Iceland</td>
<td>Nesjavellir</td>
<td>1990</td>
<td>90</td>
<td>1584</td>
<td>1450</td>
<td>611.5</td>
<td>Surface discharge with partial infield reinjection. Unused brine is discharged into the shallow boreholes or the stream. Condensed steam and cooling water are also discharged into shallow drillholes.</td>
<td>No report of reinjection returns. Initially the average enthalpy was 1700 kJ/kg, but decreased slowly to 1450 kJ/kg due to the exploitation of the field. Presently the enthalpy is rising again.</td>
<td>Axelsson et al. (2004); Bodvarsson et al. (1990); Gislason (2000); Ragnarsson (2005); Stefansson (1997); Steingrimsson et al. (2000); Wetangula and Snorrason</td>
<td>Electricity production started 1998. Heat from wastewater is also used for district heating.</td>
</tr>
<tr>
<td>Iceland</td>
<td>Svartsengi</td>
<td>1977</td>
<td>45</td>
<td>1188</td>
<td>1075</td>
<td>504</td>
<td>30-35% infield, remaining surface discharge</td>
<td>No report of reinjection returns</td>
<td>Eysteinsson (2000); Ketilsson et al. (2008); Ragnarsson (2005); Ramey Jr et al. (1985); Soltani-Hosseini et al. (2000); Stefansson (1997)</td>
<td>Waste brine is also used for direct use applications</td>
</tr>
<tr>
<td>Country</td>
<td>Field</td>
<td>Year</td>
<td>Current Generation, Mwe</td>
<td>Total Mass Produced, t/h</td>
<td>Average Enthalpy, kJ/kg</td>
<td>Reinjection Rate, t/h</td>
<td>Reinjection Strategy</td>
<td>Effects of Reinjection</td>
<td>References</td>
<td>Additional Notes</td>
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<td>--------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Indonesia</td>
<td>Sibayak</td>
<td>2000</td>
<td>2</td>
<td>1150</td>
<td></td>
<td></td>
<td>Infield reinjection</td>
<td></td>
<td>Fauzi et al. (2005); Ibrahim et al. (2005)</td>
<td>Reservoir temperature is 240-275°C.</td>
</tr>
<tr>
<td>Indonesia</td>
<td>Wayang Windu</td>
<td>1999</td>
<td>110</td>
<td>830</td>
<td></td>
<td>condensate* + 100 t/h brine</td>
<td>Infield reinjection</td>
<td></td>
<td>Fauzi et al. (2005); Ibrahim et al. (2005); Murakami et al. (2000); SKM (2004)</td>
<td>Reservoir temperature is 250-270°C. 733.3 t/h steam.</td>
</tr>
<tr>
<td>Japan</td>
<td>Hatchobaru</td>
<td>1977</td>
<td>70</td>
<td>2556</td>
<td>1125</td>
<td>1368</td>
<td>Total infield reinjection from 1977. Reinjection wells were moved 500m from the nearest production wells in 1992</td>
<td>Reinjection returns caused a temperature drop in some wells. Wells recovered once the reinjection was moved further out.</td>
<td>Kawazoe and Shirakura (2005); Matsuda et al. (2000); Stefansson (1997); Tokita, Haruguchi et al. (2000)</td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>Matsukawa</td>
<td>1966</td>
<td>23.5</td>
<td>*</td>
<td>70</td>
<td></td>
<td>Infield reinjection (Since 1988 the condensate and river water have been injected)</td>
<td>Reinjection returns, some decrease in enthalpy. It was producing superheated steam, after reinjection started half of the production wells started to produce saturated steam.</td>
<td>Fukuda et al. (2005); Hanano (2003); Kawazoe and Shirakura (2005); Stefansson (1997)</td>
<td>Reservoir temperature is 260°C.</td>
</tr>
<tr>
<td>Japan</td>
<td>Sumikawa</td>
<td>1995</td>
<td>50</td>
<td>905*</td>
<td>1300*</td>
<td>condensate + 565 t/h brine</td>
<td>Infield reinjection. Currently reinjection is being moved outfieldd and into deeper formations.</td>
<td>Reinjection returns in a few wells has caused temperature decline</td>
<td>Kawazoe and Shirakura (2005); Kumagai et al. (2004); Nedo Geothermal Energy Development Department (2003); SKM (2004)</td>
<td>340 t/h steam + 565 t/h brine. Decreased gradually from 1600 to 1300.</td>
</tr>
<tr>
<td>Country</td>
<td>Field</td>
<td>Start Date</td>
<td>Current, Generation, Mwe</td>
<td>Total Mass Produced, t/h</td>
<td>Average Enthalpy, kJ/kg</td>
<td>Reinjection Rate, t/h</td>
<td>Reinjection Strategy</td>
<td>Effects of Reinjection</td>
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<td>---------------------------------------</td>
</tr>
<tr>
<td>Mexico</td>
<td>Cerro Prieto</td>
<td>1973</td>
<td>720</td>
<td>13915</td>
<td>1350</td>
<td>2625</td>
<td>Initially total discharge into a large evaporation pond. Partial infield reinjection started in 1999. (The first injection was into shallow wells then switched to deeper zones). Currently 80% surface discharge and 20% infield reinjection.</td>
<td>Reinjection returns from the wells near to reinjection area (chemical and thermal breakthrough)</td>
<td>Gutiérrez-Negrín and Quijano-León (2005); Lippmann et al. (2004)</td>
<td></td>
</tr>
<tr>
<td>Mexico</td>
<td>Las Tres Virgenes</td>
<td>2001</td>
<td>10</td>
<td>1120</td>
<td></td>
<td></td>
<td>Infield reinjection</td>
<td></td>
<td>Gutiérrez-Negrín and Quijano-León (2005); Hinojosa et al. (2005); Hiriart and Gutiérrez-Negrín (2003)</td>
<td></td>
</tr>
<tr>
<td>New Zealand</td>
<td>Kawerau</td>
<td>1957</td>
<td>45+</td>
<td>1200</td>
<td></td>
<td></td>
<td>Partially infield reinjection</td>
<td>No reinjection returns</td>
<td>Allis (1997); Bloomer (1997); Dunstall (2005); Mroczek (2005); Stevens and Koorey (1996); Thain and Dunstall (2000)</td>
<td>Rejection started in 1991. The reinjection rate was 25%. Drilling KA39 well increased reinjection to 30%. 690 t/h is discharged into the Tarawera river. 130MWe after 2008.</td>
</tr>
<tr>
<td>New Zealand</td>
<td>Ohaaki</td>
<td>1988</td>
<td>46.7</td>
<td>1400</td>
<td>1150</td>
<td>890</td>
<td>At early times of production injection was infield and outfield. Currently outfield/edgefield reinjection is used.</td>
<td>Reinjection returns observed from infield injection. To minimise potential damage to the resource infield reinjection was stopped and edgefield outfield reinjection wells were commissioned</td>
<td>Lee and Bacon (2000); Roberts (2007); Zarrouk and O’Sullivan (2006)</td>
<td></td>
</tr>
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<td>Country</td>
<td>Field</td>
<td>Start Date</td>
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<td>Total Mass Produced, t/h</td>
<td>Average Enthalpy, kJ/kg</td>
<td>Reinjection Rate, t/h</td>
<td>Reinjection Strategy</td>
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<td>References</td>
<td>Additional Notes</td>
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<tr>
<td>Philippines</td>
<td>Mahanagdong</td>
<td>1997</td>
<td>198</td>
<td>4300</td>
<td>1481</td>
<td>2900</td>
<td>Infield and edgefield reinjection. Current policy is to move reinjection further from the production wells.</td>
<td>Rapid drawdown caused cool recharge. Reinjection returns. After a serious enthalpy drop in some wells the injection practice was revised and thermal recovery was observed.</td>
<td>N.D. Salonga et al. (2004)</td>
<td></td>
</tr>
<tr>
<td>Country</td>
<td>Field</td>
<td>Start Date</td>
<td>Current Generation, Mwe</td>
<td>Total Mass Produced, th</td>
<td>Average Enthalpy, kJ/kg</td>
<td>Reinjection Rate, th</td>
<td>Reinjection Strategy</td>
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<tr>
<td>Guatemala</td>
<td>Zunil</td>
<td>1999</td>
<td>24</td>
<td>1750</td>
<td>Total infield injection</td>
<td>unknown</td>
<td></td>
<td></td>
<td>Asturias (2003); Manzo (2005)</td>
<td></td>
</tr>
<tr>
<td>Iceland</td>
<td>Krafla</td>
<td>1977</td>
<td>60</td>
<td>986.4</td>
<td>1825</td>
<td>175</td>
<td>About half of the effluent is being reinjected infield. The other half is surface discharge.</td>
<td>Rejection returns (Tracer returns)</td>
<td>Ármannsson (2005); Gudmundsson and Arnórsson (2002); Nielsen et al. (2000); Ragnarsson (2005); Stefansson (1997)</td>
<td>Steam is also used for industrial applications. For wells N-11 and N-12 enthalpy was about 2300 kJ/kg in 1982. It has declined and was 1700–1850 kJ/kg in 1997 (with the effect of cold water recharge)</td>
</tr>
<tr>
<td>Iceland</td>
<td>Namafjall</td>
<td>1969</td>
<td>3</td>
<td>1532</td>
<td>N/A</td>
<td></td>
<td>The effluent is discharged into a pond but then seeps into the lava field.</td>
<td>N/A</td>
<td>Ármannsson (2005); Ármannsson et al. (2000); Gudmundsson and Arnórsson (2002); Ragnarsson (2005)</td>
<td></td>
</tr>
<tr>
<td>Indonesia</td>
<td>Dieng</td>
<td>1994</td>
<td>60</td>
<td>2095</td>
<td>Infield injection</td>
<td></td>
<td></td>
<td></td>
<td>Fauzi et al. (2005); Ibrahim et al. (2005); Layman et al. (2002)</td>
<td>Recent development (commissioned in 1998)</td>
</tr>
<tr>
<td>Indonesia</td>
<td>Gunung Salak</td>
<td>1994</td>
<td>330</td>
<td>11520</td>
<td>1842</td>
<td>9540</td>
<td>Total infield reinjection</td>
<td></td>
<td>Ganda et al. (1992); Ibrahim et al. (2005); Soeparjadi et al. (1998); Williamson et al. (2001)</td>
<td>Recent development (commissioned in 1997)</td>
</tr>
<tr>
<td>Country</td>
<td>Field</td>
<td>Start Date</td>
<td>Current Generation, MWe</td>
<td>Total Mass Produced, t/h</td>
<td>Average Enthalpy, kJ/kg</td>
<td>Reinjection Rate, t/h</td>
<td>Reinjection Strategy</td>
<td>Effects of Reinjection</td>
<td>References</td>
<td>Additional Notes</td>
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<td></td>
</tr>
<tr>
<td>Italy</td>
<td>Mt. Amiata</td>
<td>1962</td>
<td>111.5</td>
<td>Total Infield reinjection</td>
<td></td>
<td></td>
<td></td>
<td>Cappetti et al. (2000); Loppi (1997)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>Kakkonda</td>
<td>1978</td>
<td>80</td>
<td>2750</td>
<td>2000</td>
<td>2330</td>
<td>First 13 years total shallow infield reinjection. Then additional injection wells were drilled about 1.5 km away from the production area.</td>
<td>Arihara et al. (1995); Kawazoe and Shirakura (2005); McGuinness et al. (1995); Sato et al. (2005); SKM (2004); Stefansson (1997)</td>
<td>From 1978 until 1990, (only for 50 MWe) average 2990 t/h production, 2626 t/h injection.</td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>Onuma</td>
<td>1974</td>
<td>9.5</td>
<td>1613</td>
<td>400</td>
<td></td>
<td>Total shallow infield reinjection</td>
<td>Ishii (1986); Kawazoe and Shirakura (2005); Shigeno et al. (1993); SKM (2004)</td>
<td></td>
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</tr>
<tr>
<td>Japan</td>
<td>Yamagawa</td>
<td>1995</td>
<td>30</td>
<td>1000-2400</td>
<td></td>
<td></td>
<td>Total infield injection. Separated hot waters are divided into two hot-water lines (neutral and acidic water lines) and reinjected in order to avoid precipitation of silica scale.</td>
<td>Kawazoe and Shirakura (2005); Yagi et al. (2000)</td>
<td></td>
<td></td>
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<tr>
<td>Japan</td>
<td>Yanaizu-Nishiyama</td>
<td>1995</td>
<td>65</td>
<td>750</td>
<td>250</td>
<td></td>
<td>Total injection</td>
<td>Horikoshi et al. (1998); Kawazoe and Shirakura (2005)</td>
<td>Reservoir temperature is 270-320°C Production and reinjection rates are based on 1998 data</td>
<td></td>
</tr>
<tr>
<td>Country</td>
<td>Field</td>
<td>Start Date</td>
<td>Current, Mwe</td>
<td>Total Mass Produced, t/h</td>
<td>Average Enthalpy, kJ/kg</td>
<td>Reinjection Rate, t/h</td>
<td>Reinjection Strategy</td>
<td>Effects of Reinjection</td>
<td>References</td>
<td>Additional Notes</td>
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</tr>
<tr>
<td>Kenya</td>
<td>Olkaria I N.</td>
<td>1981</td>
<td>45</td>
<td>1023</td>
<td>2270</td>
<td></td>
<td>Surface discharge with partial infield reinjection (in 2002 10% of total brine was being reinjected) Most of the geothermal wastewater is disposed off by deep reinjection. Cold and hot reinjection has been tried.</td>
<td>Because it was causing an enthalpy drop, cold reinjection was stopped and the affected wells started recovering. Hot reinjection of separated brine has been going on since 1995. Hot brine reinjection resulted in an improvement in production wells without causing excessive enthalpy decline.</td>
<td>Kariuki and Ouma (2002); Kubo (2003); Mwangi (2005); Ofwona (2003), (2005)</td>
<td></td>
</tr>
<tr>
<td>Kenya</td>
<td>Olkaria III (West)</td>
<td>2000</td>
<td>12</td>
<td>2025</td>
<td></td>
<td></td>
<td>Infield reinjection</td>
<td></td>
<td>Hole and Kaplan (2002); Ofwona (2003); Schochet and Reiss (2001)</td>
<td></td>
</tr>
<tr>
<td>Mexico</td>
<td>Los Azufres</td>
<td>1982</td>
<td>188</td>
<td>2521</td>
<td>2220</td>
<td>530</td>
<td>Infield reinjection. 50% of total produced fluid is injected.</td>
<td>Chemical breakthrough at the production wells near to reinjection at south zone. No report on changes in thermodynamic conditions.</td>
<td>Barragán et al. (2005); Gutiérrez-Negrín and Quijano-León (2005); Torres-Rodríguez et al. (2005)</td>
<td>280 t/h waste water are sent to the binary cycle units before to be carried to the injection system</td>
</tr>
<tr>
<td>Mexico</td>
<td>Los Humeros</td>
<td>1990</td>
<td>35</td>
<td>627.6</td>
<td>2595</td>
<td>102</td>
<td>Total infield reinjection</td>
<td>The reservoir temperature decreased in the south zone of the field where intensive reinjection takes place.</td>
<td>Barragán et al. (2003); García-Gutiérrez et al. (2002); Gutiérrez-Negrín and Quijano-León (2004), (2005); Hiriart and Gutiérrez-Negrín (2003)</td>
<td></td>
</tr>
<tr>
<td>New Zealand</td>
<td>Mokai</td>
<td>2000</td>
<td>55</td>
<td>844</td>
<td>1525</td>
<td>860 brine + condensate</td>
<td>Total infield reinjection</td>
<td>No reinjection returns</td>
<td>Bromley (2003); Bromley et al. (2004); Dunstall (2005); Hunt and Graham (2004); Legmann and Citrin (2001); Menzies et al. (2001); Newson (1997); Thain and Dunstall (2000)</td>
<td>Steam flow rate 308 t/hr, NCG flow rate 4 t/hr,</td>
</tr>
<tr>
<td>New Zealand</td>
<td>Rotokawa</td>
<td>1997</td>
<td>31</td>
<td>443</td>
<td>1750</td>
<td></td>
<td>Total infield reinjection</td>
<td></td>
<td>Bromley (2003); Dunstall (2005); Legmann and Sullivan (2003); Reyes et al. (2002); SKM (2004)</td>
<td></td>
</tr>
<tr>
<td>Country</td>
<td>Field</td>
<td>Start Date</td>
<td>Current Generation, MwE</td>
<td>Total Mass Produced, t/h</td>
<td>Average Enthalpy, kJ/kg</td>
<td>Reinjection Rate, t/h</td>
<td>Reinjection Strategy</td>
<td>Effects of Reinjection</td>
<td>References</td>
<td>Additional Notes</td>
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</tr>
<tr>
<td>Philippines</td>
<td>Bacon-Manito (Bacman)</td>
<td>1993</td>
<td>150</td>
<td>2590</td>
<td>1990</td>
<td>1494</td>
<td>Infield and edgefield reinjection</td>
<td>No reinjection returns</td>
<td>Benito et al. (2005); Relativo-Fajardo et al. (1999)</td>
<td></td>
</tr>
<tr>
<td>Philippines</td>
<td>Bulalo (Mak-Ban)</td>
<td>1979</td>
<td>425.73</td>
<td>6901</td>
<td>1900</td>
<td>2812</td>
<td>Initially total infield reinjection. Presently edge-field injection with total condensate and 60% of total brine</td>
<td>Infield reinjection returns caused thermal breakthrough. Reduction of infield reinjection resulted in gradual recovery in many wells.</td>
<td>Benito et al. (2005); Clemente and Valladolid-Abrigo (1993); Sta. Maria et al. (1995)</td>
<td></td>
</tr>
<tr>
<td>Philippines</td>
<td>Mindanao</td>
<td>1996</td>
<td>108.48</td>
<td>2160</td>
<td>1500</td>
<td>1260</td>
<td>Mixed infield and outfield reinjection. Recently a recommendation was given to change to outfield reinjection.</td>
<td>Reinjection returns was detected in 1998. Thermal breakthrough occurred. But constant rate of production and reinjection caused thermal recovery.</td>
<td>Benito et al. (2005); Esberto et al. (2001); Nogara et al. (2005); Trazona et al. (2002)</td>
<td></td>
</tr>
<tr>
<td>PNG</td>
<td>Lihir</td>
<td>2003</td>
<td>36</td>
<td>830</td>
<td>2250</td>
<td>N/A</td>
<td>Surface discharge</td>
<td>N/A</td>
<td>Booth and Bixley (2005); Melaku (2005); White et al. (2006)</td>
<td></td>
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<tr>
<td>Russia</td>
<td>Mutnovsky-Kamchatka</td>
<td>1999</td>
<td>62</td>
<td>1118</td>
<td>1600</td>
<td></td>
<td>Total infield reinjection</td>
<td></td>
<td>Kononov and Povarov (2005); Povarov et al. (2002); SKM (2004)</td>
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Table 5. Two-phase, vapor dominated reservoirs

<table>
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<tr>
<th>Country</th>
<th>Field</th>
<th>Start Date</th>
<th>Current Generation, Mwe</th>
<th>Total Mass Produced, t/h</th>
<th>Average Enthalpy, kJ/kg</th>
<th>Reinjection Rate, t/h</th>
<th>Reinjection Strategy</th>
<th>Effects of Reinjection</th>
<th>References</th>
<th>Additional Notes</th>
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<tbody>
<tr>
<td>Indonesia</td>
<td>Darajat</td>
<td>1994</td>
<td>145</td>
<td>907.2</td>
<td>2783</td>
<td>1450 *</td>
<td>Total Infield reinjection + surface water.</td>
<td>Tracer testing showed tracer breakthrough in five production wells within 5-12 days.</td>
<td>Alamsyah (1999); Alamsyah et al. (2005); Ganda et al. (1992); Hoang et al. (2005); Ibrahim et al. (2005); Soekono (1996)</td>
<td>Condensed steam + surface water reinjection. 259 MWe after 2007.</td>
</tr>
<tr>
<td>Italy</td>
<td>Larderello</td>
<td>1913</td>
<td>542.5</td>
<td>3060</td>
<td>2770</td>
<td></td>
<td>Infield reinjection started in early 1970's. From 1983 shallow infield reinjection.</td>
<td>No reinjection returns. Reinjection plays an important role in recharge.</td>
<td>Cappetti and Lio Ceppatelli (2005); Cappetti et al. (1995); Cappetti and Stefani (1994)</td>
<td>The amount of condensates and supplementary water reinjected is much less than mass produced.</td>
</tr>
<tr>
<td>Italy</td>
<td>Travale / Radicondoli</td>
<td>1973</td>
<td>160</td>
<td>1080</td>
<td>2800 *</td>
<td></td>
<td>Infield reinjection started in 1979 to decrease pressure drawdown and subsidence, but only applied for few years</td>
<td>N/A</td>
<td>Cappetti and Lio Ceppatelli (2005); Di Filippo et al. (1985); Di Filippo et al. (1995)</td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>Uenotai</td>
<td>1994</td>
<td>27.5</td>
<td>260</td>
<td>2800</td>
<td></td>
<td>Infield reinjection started in 1993. Since reinjection returned and caused a temperature decrease to avoid further mixing of waste water into production, reinjection was moved out.</td>
<td>After one and a half years reinjection returned and this caused enthalpy drop in some wells. Wells recovered once the reinjection moved.</td>
<td>Butler et al. (2005); Hisatani et al. (2000); Nakao et al. (2007); Tamanyu et al. (1998)</td>
<td>*During injection enthalpy dropped from 2800 to as low as 1600 kJ/kg then recovered when it stopped.</td>
</tr>
<tr>
<td>Country</td>
<td>Field</td>
<td>Start Date</td>
<td>Current, Mwe</td>
<td>Total Mass, t/h</td>
<td>Average Enthalpy, kJ/kg</td>
<td>Reinjection Rate, t/h</td>
<td>Reinjection Strategy</td>
<td>Effects of Reinjection</td>
<td>References</td>
<td>Additional Notes</td>
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</tr>
<tr>
<td>New Zealand</td>
<td>Pohipi</td>
<td>1998</td>
<td>25</td>
<td>200</td>
<td>2750</td>
<td>70</td>
<td>Total outfield reinjection</td>
<td>No effect</td>
<td>PB Power (2001); Zarrouk et al. (2006)</td>
<td>Increased in enthalpy as a result of large increase in production. From about 1800kJ/kg to dry steam enthalpy 2700kJ/kg in Tongonan 1 and Upper Mahiao.</td>
</tr>
<tr>
<td>Philippines</td>
<td>Tongonan (Lyte)</td>
<td>1983</td>
<td>468.5</td>
<td>6850</td>
<td>2600</td>
<td>2850</td>
<td>Total infield reinjection in 1983. Reinjection was moved outfield during the early years of production.</td>
<td>Reinjection returns from infield reinjection (chemical and thermal breakthrough). Wells recovered once infield reinjection was relocated further out.</td>
<td>Bayon and Ogena (2005); Bolaños and Parrilla Jr (2000); N. D Salonga et al. (2004)</td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>The Geysers California Department of Conservatio n</td>
<td>1960</td>
<td>1000</td>
<td>7200</td>
<td>1900-2700</td>
<td>6150</td>
<td>Total infield reinjection. 1970s condensate reinjection. In 1997 additionally secondary treated waste water 1455 t/h started. In 2004 tertiary treated water 1750t/h (but 1450 t/h only in dry spring session)</td>
<td>Thermal breakthrough forced the reduction of reinjection rate and relocation of reinjection wells</td>
<td>Goyal (1998); Goyal (2004); Lund et al. (2005); Sanyal (2000); Stark et al. (2005); Stefansson (1997)</td>
<td>With the last recharge project (SRGRP) mass replacement rate is up to 80%.</td>
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## Table 6. Unclassified reservoirs

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<th>Country</th>
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<th>Total Mass Produced, t/h</th>
<th>Average Enthalpy, kJ/kg</th>
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<th>Reinjection Strategy</th>
<th>Effects of Reinjection</th>
<th>References</th>
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<tbody>
<tr>
<td>China</td>
<td>Fengshun (Guangdong)</td>
<td>1984</td>
<td>0.3</td>
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<td></td>
<td></td>
<td></td>
<td>Zheng et al. (2005)</td>
</tr>
<tr>
<td>China</td>
<td>Huitang (Hunan)</td>
<td>1975</td>
<td>0.3</td>
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<td>Zheng et al. (2005)</td>
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<tr>
<td>Japan</td>
<td>Suginoi</td>
<td>1981</td>
<td>3</td>
<td></td>
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<td></td>
<td>Kawazoe and Shirakura (2005)</td>
</tr>
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<td>Japan</td>
<td>Hachijyojima</td>
<td>1999</td>
<td>3.3</td>
<td></td>
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<td>Kawazoe and Shirakura (2005)</td>
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<tr>
<td>Russia</td>
<td>Okeansky (Kuril Islands)</td>
<td>1999</td>
<td>3.4</td>
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<td>Kononov and Povarov (2005)</td>
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<td>Russia</td>
<td>Goryachii Plyazh (Kuril Islands)</td>
<td>2004</td>
<td>2.6</td>
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<td>Kononov and Povarov (2005)</td>
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<td>USA</td>
<td>Desert Peak (Nevada)</td>
<td>1985</td>
<td>12.5</td>
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<td>Lund et al. (2005)</td>
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Puna Geothermal Venture Hawaii. from www.punageothermalventure.com


References


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