The Sustainability of Geothermal Energy

Under what conditions is a geothermal system used sustainably?

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MSc Graduation Thesis
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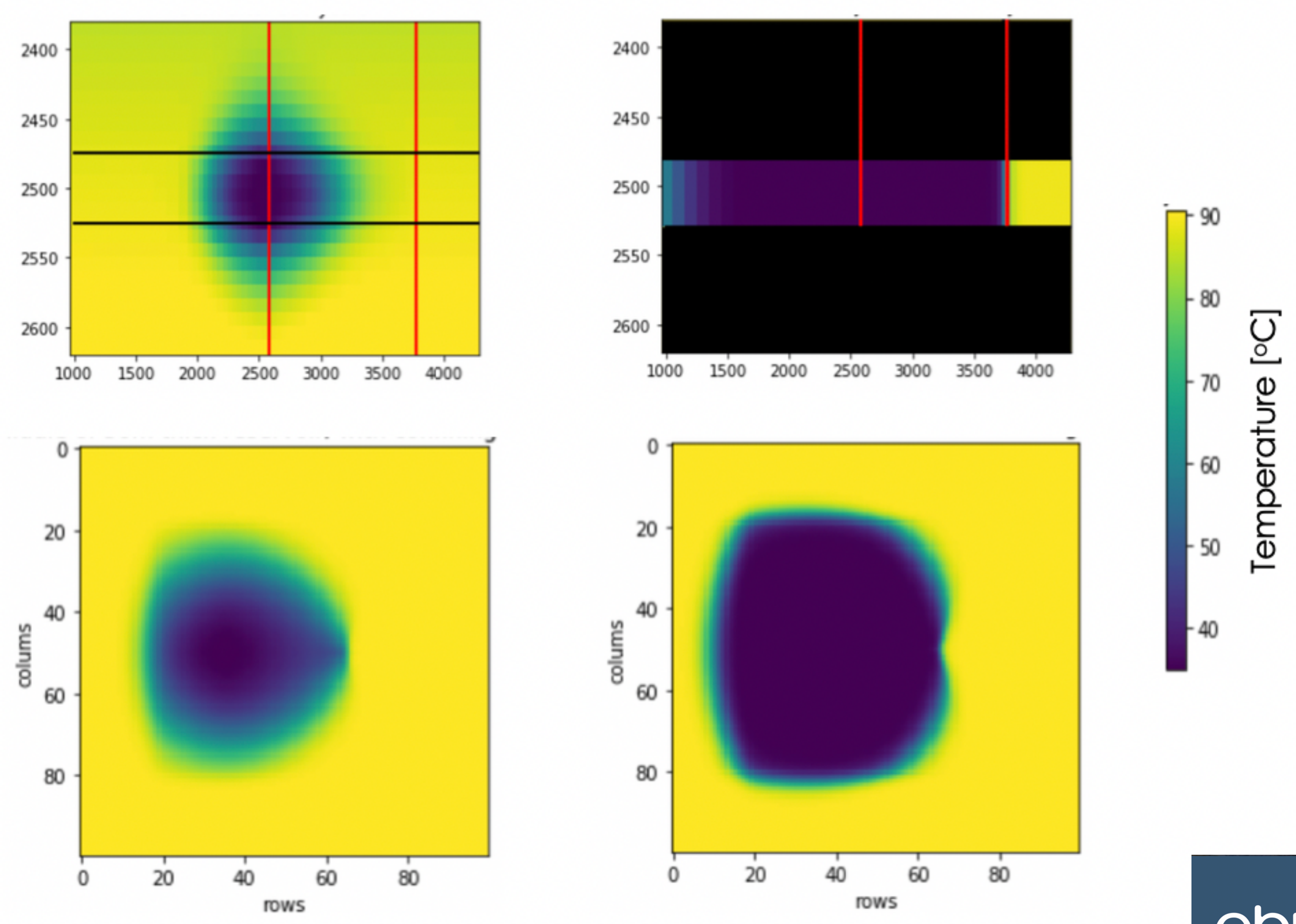

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by

Esmée de Bruijn

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Abstract

Geothermal energy is generally seen as a sustainable source of energy and therefore could be part of the solution for the energy transition. However, there is still a lack of clarity about the conditions under which a geothermal system can be used sustainably.

This study investigates the sustainable use of a geothermal system. The geothermal production process in a homogeneous geothermal reservoir with one doublet was simulated using SEAWAT. This model provides the possibility to conduct a sensitivity analysis to examine which parameters play an important role in the geothermal production process. The aim of this analysis was to asses the effect on the well temperature and the thermal recharge, i.e. heat flow from the confining layers towards the reservoir. The tested parameters include four geological uncertainties and two production parameters.

From the tested geological uncertainties the thickness of the reservoir has the largest effect on the production profile. Also, it has an impact on the effect of all the other parameters tested, especially on the effect of the confining layers. The confining layers play an important role during the simulation of the production process because they control the thermal recharge, and this enhances the lifetime of the geothermal project. The thinner the reservoir, the larger is the effect of the confining layers and the change in its properties and the more impact the thermal recharge has on the production profile.

By examining the effect of the production parameters, the aim was to define a sustainable production design and strategy. It was proven that the production rate has a large impact on the lifetime of a geothermal project, and that an increasing well spacing enhances the sustainable use of a geothermal system. To enhance the sustainable extraction of geothermal energy from a geothermal system the production rate should be kept low. When making a production optimisation two rules of thumb apply to maintain a sustainable production. The first rule says that with a doubling of the reservoir thickness, the production rate can be increased by approximately 50%. The second rule says that with an increase of well spacing of 20%, the production rate can be increased by approximately 50%.

Overall, this study emphasizes the positive effect of thermal recharge on the production profile and its enhancement on the sustainable use of a geothermal system. We can conclude that with a sustainable production design and strategy the production from a geothermal system can continue for generations.

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This thesis is the final project to obtain a Master in Petroleum Engineering and Geosciences, and marks the end of my studies at Delft University of Technology. Working on this project for the past nine months has been a challenging but rewarding experience, which I could not have done without some help and support along the way. Therefore, I would like to thank those who have been involved with this project an my studies. First of all, I would like to thank my TU Delft supervisors Femke Vossepoel and Martin Bloemendal. Femke has guided me throughout entire process, from helping to find a subject to the last piece of feedback. She was always willing to help despite her busy schedule. Martin, thank you for helping me with all my problems regarding the simulation software and for your useful the thermal processes in the subsurface.

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Esmée de Bruijn
Delft, May 2020

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Nomenclature

The next list describes several symbols that will be later used within the body of the document

$\alpha\frac{q}{\theta}$	Dispersion	[-]
α	Dispersion tensor	[m]
α_L	Longitudinal dispersivity tensor	[m]
α_T	Transverse dispersivity tensor	[m]
ΔE	Time-integrated change in energy content of the reservoir	[J]
ΔE_i	Time-integrated change in thermal energy content of cell i	[J]
ΔE_x	Change in thermal energy content between timestep x and x-1	[J]
Δt	Length of a timestep	[s]
Δx	Grid spacing	[m]
λ	Thermal conductivity	[W/m/K]
λ_f	Fluid thermal conductivity	[W/m/K]
λ_s	Matrix thermal conductivity	[W/m/K]
μ	Viscosity	[kg/m/s]
μ_0	Dynamic viscosity at reference concentration and temperature	[kg/m/s]
$\nabla\varphi$	Concentration gradient	[-]
∇T	Difference in temperature over a certain distance	[K]
∇	Gradient vector in x,y,z direction	[-]
ρ_0	Fluid density at reference concentration and temperature	[kg/m^3]
ρ_b	Bulk density	[kg/m^3]
ρ_f	Fluid density	[kg/m^3]
ρ_s	Matrix density	[kg/m^3]
ρ_{bi}	Bulk density of cell i	[kg/m^3]
θ	Porosity	[-]
C^k	Concentration of solute k	[kg/m^3]
C_s^k	Concentration of solute k in the source	[kg/m^3]
c_b	Bulk specific heat capacity	[J/kg/K]
c_f	Fluid heat capacity	[J/kg/K]
c_s	Matrix heat capacity	[J/kg/K]
c_{bi}	Bulk volumetric specific heat capacity of cell i	[J/K/m^3]
D_{diff}^k	Molecular diffusion coefficient of solute k	[m^2/s]
D_H	Thermal diffusivity	[m^2/s]
E_p	Time-integrated produced energy	[J]
E_r	Thermal energy content of the reservoir	[J]

g	Gravitational constant	[m^2/s]
h	Hydraulic head	[m]
h_0	Reference hydraulic head	[m]
J	Diffusion flux	[-]
K	Hydraulic conductivity	[m/s]
k	Permeability	[m^2]
K_d^k	Distribution factor of solute k	[m^3/kg]
K_0	Hydraulic conductivity tensor of material saturated with reference fluid	[m/s]
K_d	Thermal distribution factor	[m^3/kg]
P	Power	[W]
Pe	Peclet number	[-]
Q	Volumetric production rate	[m^3/hr]
q	Specific discharge vector	[m/s]
$q_s^{'}$	Source or sink of fluid	[m^3/hr]
q_h	Heat flow	[W/m^2]
R_t	Retardation factor	[-]
$S_{s,0}$	Specific storage	[m$^-$1]
t	time	[s]
T_i	Time-integrated temperature in cell i	[K]
T_r	Characteristic temperature	[K]
T_s	Temperature in the source	[K]
T_x	Temperature at timestep x	[K]
$T_{i,ini}$	Initial temperature of cell i	[K]
T_{inj}	Injection temperature	[K]
T_{prod}	Production temperature	[K]
T_{ref}	Reference temperature	[K]
V	Volume	[m^3]
V_i	Volume of cell i	[m^3]

1

Introduction

1.1. Geothermal Energy

In the Paris agreement of 2015, the Dutch government agreed to reduce the CO_2 emission in the coming years. Emissions must be reduced by 40% and 95% compared to 2015 in respectively 2030 and 2050. To achieve this goal, the energy supply in the Netherlands needs to shift from fossil fuels to sustainable and renewable sources. Wind and solar energy are the best known and most used options to generate electricity in a sustainable way. In addition to that, geothermal energy is one of the energy sources that is generally considered to be a renewable option (Schoof et al., 2018). The Dutch government also considers geothermal energy to be part of the solution for the energy transition.

In this section, a short introduction will be given to explain what geothermal energy is. Subsequently, the complications regarding geothermal energy will be discussed, and the questions thus raised will be addressed.

Firstly, we will give a short introduction to geothermal energy. Geothermal energy is a form of energy that is based on the internal heat of the Earth. Hot water is extracted from the subsurface and brought to the surface, where it can be directly used for heating greenhouse horticulture or buildings, or to generate electricity. The thermal energy that is present within the subsurface of the Earth is called geothermal energy. This form of energy is produced from a geothermal system. A geothermal project makes it possible to produce geothermal energy form a geothermal system. An overview of these three concepts is provided by Figure 1.1.

Figure 1.1: A schematic overview of the differences between geothermal energy, system and project

When geothermal energy in the form of hot water is extracted form the geothermal system, the pressure in the reservoir near the production well will drop. To maintain the pressure, as well as enhance heat recovery and ensure a safe disposal of wastewater, cooled water is injected in the same reservoir (Ganguly and Mohan Kumar, 2014), using an injection well. The injection and producing well together form one doublet. The water that is used to inject into the reservoir, is the produced geothermal water from which the heat has been extracted. With constant injection of cold water, the reservoir near the injection well will start to cool down. A cold front will form which will move gradually from the injection well towards the production well. When this cold front reaches the production well, the production temperature will decrease (Ganguly and Mohan Kumar, 2014). The moment this happens is called thermal break-through. Due to the fact that the production temperature drops, the amount of energy that can be produced from the geothermal reservoir decreases. If the temperature of the produced water drops below a certain point, the production will have to be shut down. Unlike fossil fuels, geothermal energy can be recharged towards the system, which increases the lifetime of a geothermal system. The goal of a geothermal project is to sustainably use the geothermal system, to optimise the lifetime of a geothermal project.

Two aspects regarding the sustainable use of geothermal energy are still uncertain, which will cause complications when designing a geothermal project. The first aspect is the lifetime of a geothermal project. There is still a lot of uncertainty regarding the time scale in which geothermal energy can be produced. When will thermal breakthrough occur, and after how long should the geothermal system be shut down? Because this is not yet known, it is doubtful to what extent a geothermal system is sustainable.

The second aspect that is still a point of discussion, is the renewability of the resource. Because it is not yet exactly known how, to what extent, and especially in which time scale, geothermal energy resources are renewable (Rybach et al., 2000).

Previous work discusses these two aspects. Axelsson and Steingrímsson et al. have done research to investigate how reservoir management can contribute to sustainable production from a geothermal system. Poulsen et al. (2015) emphasizes the huge potential and the long lifetime of a geothermal system as a result of thermal recharge during production. However, due to the lack of hard evidence regarding the lifetime of a geothermal project, it could also be that a geothermal system cannot be used sustainably and has a production lifetime similar to that of fossil fuels.

With the the controversy of the existing studies there is still a lack of clarity on the sustainable use and renewability of a geothermal system. To address these issues, the following questions have been raised. To start with, what determines the lifetime of a geothermal system? What geological aspects have a large impact on the production process of the geothermal system? Which physical processes, that occur in the subsurface during extraction, play an important role? And what is the role of recharge and how does it affect the production process? What are the effects of a change in production design or strategy to the lifetime of a geothermal system? What production design and strategy ensures the most sustainable extraction of energy from a geothermal system? Can a geothermal system be depleted after extensive production, and should it therefore be considered as a fossil fuel? Will the demand for energy change in the coming decades and what effect will this have on the energy production from a geothermal system? These questions are the reason for this research, because it is important to get a better understanding on how a geothermal system is used sustainably.

This study addresses the sustainable use of geothermal energy from a geothermal system. It focuses on the role that the subsurface plays within a geothermal project, and how a homogeneous geothermal reservoir reacts to the production using one doublet. This will be done by answering the research questions presented in the next section.

1.2. Research Questions

The objective of this study is to examine what role geothermal energy can play during the energy transition. Therefore, the sustainable use of a geothermal system will be investigated. Central to our research is the following main research question:

Under what conditions is a geothermal systems used sustainably?

To be able to answer this question a parametric study is done to investigate the effect of a well defined set of geological uncertainties and production parameters. The sensitivity of the geothermal production process on these parameters is evaluated. With those results this thesis will answer the following three research questions:

- What are the effects of the geological uncertainties on the geothermal production profile?
- What are the effects of production parameters on the geothermal production profile?
- How can the effects of the geological uncertainties and production parameters be translated to a sustainable production design and strategy?

1.3. Previous Work

In the last decades, the research concerning geothermal energy has increased. In the papers from Steingrímsson et al. (2006) and Axelsson (2012, 2005, 2001) the sustainable use of geothermal resources and reservoir management are elaborated. Steingrímsson et al. emphasizes that a geothermal system can reach a kind of balance that may be maintained for a long time, when the production rate is kept below a certain limit. Axelsson claims that a time-scale in the order of 100-300 years should be assumed for sustainable utilization of geothermal resources. In order to control the decline in the reservoir, he suggest three different production methods; a constant production rate below the

sustainable limit, step-wise increase in production or cyclic production. The work of Steingrímsson et al. and Axelsson focuses on the sustainable development for a number of case studies. They do not investigate what the effect of a change in the geological setting is on the capacity of the geothermal system.
The effect of a number of geological and production parameters are investigated for the research of Poulsen et al. (2015). His work focuses on the effect that the thermal recharge has on the production from a geothermal system. He concludes that the well temperature decline is strongly dependent on the amount of thermal recharge, and emphasizes the importance of the modelling of the confining layers.

In this study, these two subjects will be combined to investigate what the effects are of geological and production parameters for a sustainable use of a geothermal system.

1.4. Approach

The research questions of this study will be answered using the following approach.
To start of with, we build a model of a geothermal reservoir to simulate the production process of a geothermal system. The simulation tool uses a finite difference approximation to calculate solute and heat transport in the subsurface (Langevin et al., 2007). By simulating the production process, the thermal activities that occur in the subsurface during the production from a geothermal system are investigated. This first model is based on the properties of geothermal reservoirs in the Netherlands and will be further addressed as the 'Base Case'. To investigate what the effect is of on the production process one parameter of this Base Case is altered. This can be either a geological uncertainty or a production parameter. With the results of the sensitivity analysis, we investigate the processes that occur in the subsurface and what role they play in a sustainable use of a geothermal system. This knowledge allows for a more balanced and well-considered choices of the production design and strategy when making a production optimisation. For a number of scenarios, either with a deviating geology or a different production plan, we have made a production design and strategy for a sustainable use of the geothermal system.

1.5. Thesis Outline

This thesis comprises of six chapters. This first chapter addresses the research objective and presents the research questions.

Chapter 2 provides background information regarding geothermal energy, the use of it in the Netherlands, heat transport in the subsurface and the concept of sustainability and renewability.

Chapter 3 describes the methodology of this study. First the processes that occur in the subsurface are described. Beginning by discussing the energy content of the subsurface, then the processes regarding the transport of heat and the thermal properties related to that. After that the simulation tool that is used for this study will be analyzed, and the mathematical formulations it is based on are described. Subsequently the setup of the model is presented. Finally the numerical experiments, that are conducted during this study are introduced.

Chapter 4 contains the results of these numerical experiments and the analyses conducted on these results. The experiments are divided into tests that examine the sensitivity to geological uncertainties, and tests that analyze the effect of production parameters. The results are then analyzed in the same classification.

Chapter 5 provides a production optimisation for multiple scenarios to use the geothermal system in a sustainable way.

Chapter 6 describes points of discussion that have arisen during this research. The points of discussion include; the limitations of the scope of this research; the effect of an incorrect model setup; conceptual analyses; and the requirements for a sustainable use of a geothermal system.

Chapter 7 discusses the limitations of this research and gives recommendations for further research.

Chapter 8 draws the conclusions of this study by answering the research questions.

2

Background Information

This chapter provides the necessary background information for this research. Section 2.1 gives a general overview of what geothermal energy is and how it can be produced. Section 2.2 describes the role of geothermal energy in the Netherlands. Section 2.3 explains how heat is transported within the subsurface. Section 2.4 introduces the definitions of sustainability and renewability.

2.1. Geothermal Energy

Geothermal energy may seem a new form of energy that is still in its infancy, but this is not the case. For centuries, mankind has used the Earth's heat in the form of geysers and hot springs for cooking and bathing. Only then they were unaware of the magnitude and potential of the Earth's heat capacity.

To understand where this heat comes from, a general knowledge of the Earth's structure is required. The Earth consists of three zones, the crust, mantle and core, from the exterior to the centre. The crust, the 'skin of the Earth' is the part we live on. The thickness of the crust varies between 7 km of oceanic crust, to 20-65 km thickness of continental crust (Barbier, 2002) . The mantle has a thickness of 2900 km and makes up 84% of the Earth's volume (Robertson, 2011). The core of the Earth has a radius of 3470 km. The core is divided into a liquid outer core and a solid inner core (Robertson, 2011). At this boundary, temperatures of up to 6000^{o}C occur Howell.

The high temperatures that occur within the Earth are the result of both the heat generated during the formation of the Earth, and heat that is produced since the formation. The latter source of heat is a result of the decay of radioactive isotopes in the mantle of the Earth. With the decay of these isotopes, including ^{40}K, ^{232}Th, ^{235}U and ^{238}U, heat is generated. The half lives of these isotopes are in the same order of magnitude as the age of the Earth (Barbier, 2002).

From the centre of the Earth a heat flow of approx 47 TW reaches the surface (Davies and Davies, 2010). This heat passes through the upper crust of the Earth. Moving downwards into the subsurface, the temperature of the surrounding rocks gradually increases. The rate at which the temperature increases is the geothermal gradient. The average geothermal gradient is 30^{o}C/km, with outliers from 10^{o}C to +100^{o}C for respectively ancient continental crust and areas active volcanism. Consequently, the pore fluids in the rock are heated to the same temperature as the surrounding rock.

To make use of geothermal thermal energy, the heated water is pumped out of the reservoir rock to the surface. To be able to do this, two wells are drilled, a producing and injecting well and together they form a doublet. Hot water is pumped up from the reservoir by a production well. The hot stream of water travels through a heat exchanger where the heat

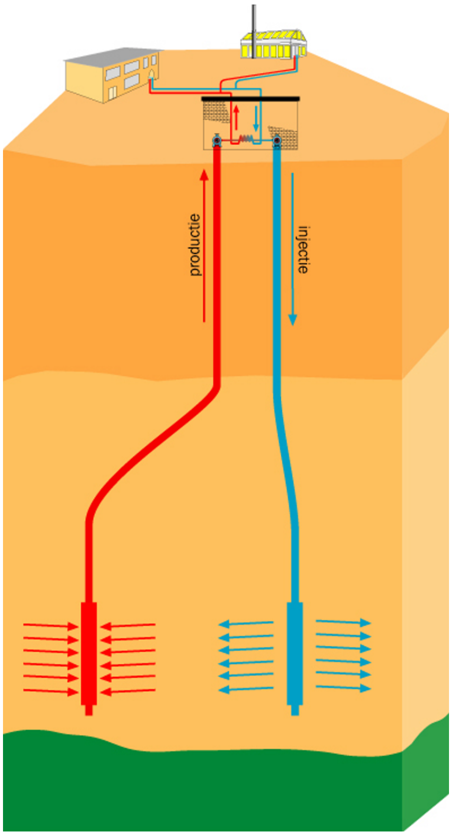


Figure 2.1: A Geothermal doublet. The red and the blue lines represent respectively the production and injection wells. At the surface a schematic overview of a heat exchanger is shown (van den Boschh et al., 2013)

is transferred. The cooled down water is pumped back into the reservoir by the injection well, to maintain pressure and prevent subsidence (Barbier, 2002). The geothermal installation at the surface is designed to be able to transfer heat at a certain range of temperatures. Figure 2.1 shows a schematic overview of a doublet and a heat exchanger.

2.2. Geothermal Energy in the Netherlands

The energy mix in the Netherlands currently consists of 10% of renewable energy (EBN, 2020). With the aim of meeting the Paris agreement requirements, the Dutch government considers geothermal energy as a possible way of lowering the fossil fuel dependency and increasing the renewable energy share (Schoof et al., 2018).

At this moment, 17 geothermal doublets are active in the Netherlands. An overview of the locations of all the doublets is shown in Figure 2.2 Together they produce approx. 3PJ of heat. The goal is that in 2030 5% of the total energy demand (930 PJ) will be produced using geothermal energy. In 2050, 23% of the total energy demand should consist of geothermal heat. This comes down to 200 PJ of geothermal energy, that will be produced by 700 doublets. To meet those requirements, the development of geothermal installations would have to increase in the coming years. Simultaneously, more than 100.000 houses would have to be connected to the district heating network every year, so that in 2050 four million households will be connected and heated with geothermal heat (Schoof et al., 2018).

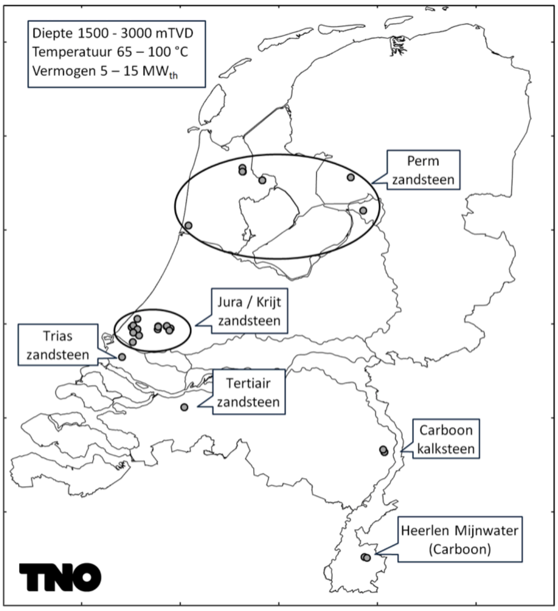


Figure 2.2: A overview of the installed doublets in the Netherlands. (TNO, 2018)

2.3. Heat transport in the subsurface

Heat can be transported in three different ways: radiation, convection and conduction. In the subsurface, mainly convection and conduction occur.

Convection is a heat transfer process that occurs mostly in liquids and gasses and consists of movement of fluids and gasses from one place to another caused by a difference in buoyancy.

Conduction uses the principle of kinetic energy to transfer heat. The movement of molecules causes transfer of heat. Conduction of heat mostly occurs in solids, and generally speaking, metals are good conductors of heat whereas rocks are poor conductors. Within the different zones of the Earth, generally, heat transfer based on convection occurs in the liquid outer core, and heat transfer based on conduction occurs in the solid mantle and outer core, due to their solid character. Both the convection and the conduction of heat occur in the crust and play an important role during the production from a geothermal reservoir.

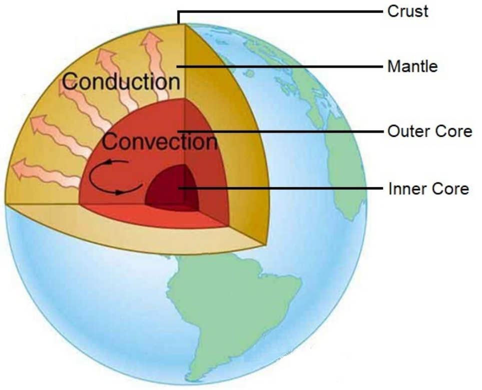


Figure 2.3: Heat transfer from the inner core to the outer core, mantle and crust takes place through convection and conduction.

A schematic overview of the zones of the Earth and their main types of heat transfer is shown in Figure 2.3.

2.4. Sustainability and Renewability

To assess how a geothermal system can be used sustainably and how the renewability of the resource can contribute to it, a clear understanding is required of these two concepts and how we use them differently in this thesis.

Sustainability and renewability are two terms that are often confused, or thought to be one and the same thing. There is however a great difference between these two concepts. The renewability of a system describes the ability to replace the resource that has been produced. Therefore, it is a property of the resource. The sustainability of a system depends on how the resource is produced and how the system responds to that. Therefore, it is a property of the production. (Steingrímsson et al., 2006).

In order to determine the sustainability and renewability of a geothermal energy source, the definitions of those concepts should be considered. First the sustainability will be discussed, followed by renewability.

Sustainability

Sustainability explains the way a resource is produced. Therefore, it is addressed as sustainable development. The concept of sustainable development is a difficult concept to define and it depends on the process it is used for. The World Commission on Environment and Development (1988) uses the following description:

> *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*

In this definition, the fact that the needs of future generations may vary in time, is not taken into account. Nor are technical improvements considered that will change the development of the resources. Therefore, this definition gives more of a political description than a scientific explanation. In literature, various analyses regarding sustainable development exist. With those analyses, a better image of what can be considered as sustainable geothermal development can be obtained. Generally, the development of a project is considered to be sustainable when the project lasts a long time compared to the economical time constants of that project (Steingrímsson et al., 2006). For a geothermal system, sustainable use is considered to be between 100 and 300 years in Iceland (Axelsson et al., 2005) and more than 100 years in New Zealand (Bromley et al., 2006). What sustainable development of a geothermal system in the Netherlands is, is not still not clear. Therefore, in Section 6.4 of this study we define what sustainable development for a geothermal system means. Taking into account all the factors that play a role during the development of a geothermal system.

Renewability

Renewability is a less subjective concept than sustainability. Because renewability is a property of the resource, it is easier to define. Only the time scale of renewability, i.e. the time it takes for the subsurface to return to its original state, is a subject for discussion. Axelsson et al. (2001) defines a renewable energy source as follows:

> *The energy extracted from a renewable energy source is always replaced in a natural way by an additional amount of energy and the replacement takes place on a similar time scale as that of the extraction.*

With this definition Axelsson et al. (2001) states that all the energy that is extracted, should be replaced within the same time scale as its production lasted. The recovery of the geothermal system, is based on the recharge of geothermal energy towards the system, so that the system returns to its original state. After the production stops, the recovery shows an asymptotic behaviour, it is fast to begin with, and later it slows down. In the same time scale as the production, the original state of the energy content that the reservoir had, can be approached. Fridleifsson et al. (2008) declares that it will take an infinite amount of time for the geothermal system to return to its original state. However, 95% of the recharge will occur on a time scale of the same order as the geothermal production lifetime (Axelsson et al., 2005). The degree of renewability, and the rate at which the energy is recharged to the geothermal system, contributes to the sustainable use of the geothermal system. The renewability of a geothermal system will be further discussed in Section 5.3.

The difference between sustainability and renewability follows from the definitions above. Sustainability says something about the production process, and renewability is a property of the resource. The more renewable the resource is, the more sustainably it can be produced. The existing definition of sustainable development still leaves plenty of room for discussion. There is not yet one clear definition that is focused on geothermal energy production. With the results obtained from this study, we can asses what the sustainable development of a geothermal system in the Netherlands means. This will be further discussed in Section 6.4.

3

Methodology

This study uses a model to simulate a geothermal production process. This chapter discusses the properties and processes that play a role in the subsurface and are of importance to build a representative model of the Dutch subsurface. This chapter consist of 5 sections:

Section 3.1 discusses the energy content of the reservoir. It is important to understand how much energy is stored within the subsurface and what amount can be extracted using a geothermal system, in order to determine the right production strategy.

Section 3.2 discusses the processes that play a role in the transport of heat in the subsurface. It is important to understand how heat flows through the subsurface in order to understand why certain parameters have effect on the thermal production process.

Section 3.3 elaborates on the simulation tool which is used to build the model and simulate the geothermal processes, and explains the equations that represent the physics in the subsurface.

Section 3.4 contains the model setup, it summarizes all of the input parameters used for the reservoir simulation.

Section 3.5 elaborates on the conducted experiments and the assessment frameworks used for this research.

3.1. Energy Content of a Reservoir

This section features the thermal energy content of the subsurface. It discusses how much thermal energy is stored within a reservoir, and how much of that energy can be produced.

Firstly we will discuss the heat capacity, a thermal property that determines the energy stored in the subsurface. Secondly, the thermal energy content of a geothermal system will be examined. The third subsection analyzes the thermal energy available in a reservoir. The fourth discussed subject is the produced energy from the geothermal system. Finally we explain the concept of energy recharge.

3.1.1. Heat Capacity of the subsurface

Heat capacity is the property that indicates the amount of heat that is necessary to raise the temperature of a unit volume (1 m^3) or weight (1 kg) by 1 ^{o}K. During the temperature rise, the material should remain in the same phase. Heat capacity is expressed in energy per unit weight for every one degree change in temperature[J/kg/K]. If the heat capacity of a substance is measured in volume, it is called volumetric heat capacity [J/m^3/K]. Equation 3.1 shows how volumetric heat capacity is determined:

$$\rho c = \rho * c, \tag{3.1}$$

with c the heat capacity [J/kg/K], ρ the density of the material [kg/m^3] and ρc the volumetric heat capacity [J/m^3/K].

Generally, the volumetric heat capacity of water is higher than the volumetric heat capacity of rocks. Figure 3.1 shows a schematic overview of the volumetric heat capacity of sandstone and water, the arrows indicate the amount of energy required to heat one cubic meter of the material by one degree. This figure reveals that it takes

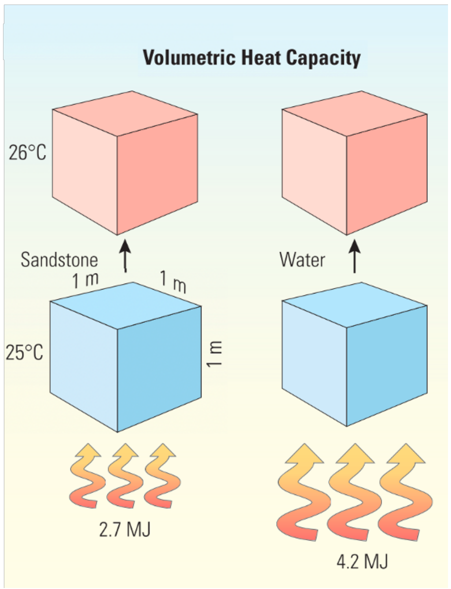


Figure 3.1: Volumetric heat capacity for 1m^3 of Sandstone and Water. (Chekhonin et al., 2012)

only two thirds of the amount of energy to raise the temperature of one cubic meter of sandstone compared to one cubic meter of water.

The subsurface is often a mixture of matrix rock and pore fluid. The matrix consists of sandstone and the pores are filled with water. The properties of this porous medium, are compiled from the properties of the matrix rock and the pore fluid. Together they form the bulk property. The bulk property can be calculated using the following equation:

$$x_b = \theta x_f + (1-\theta)x_s, \tag{3.2}$$

with x_b the bulk value of property x, x_f the fluid value of property x, x_s the matrix value of property x and θ the porosity.

The bulk volume heat capacity ρc_b is calculated in the following manner(Nick, 2017):

$$\rho c_b = \theta \rho_f c_f + (1-\theta)\rho_s c_s, \tag{3.3}$$

where c_f and c_s are respectively the heat capacity of the pore fluid and the matrix rock [J/kg/K] and ρ_f and ρ_s the pore fluid density and matrix density [kg/m^3]. The bulk heat capacity is necessary to determine the energy content of a geothermal reservoir.

3.1.2. Energy content

In order to predict the amount of the energy that can be produced from a geothermal reservoir, the energy that is stored within the geothermal reservoir should be determined. Using Equation 3.4 the energy content of a reservoir can be approximated as follows (Franco and Donatini, 2017):

$$E_r = \rho_b \cdot c_b \cdot V \cdot (T_r - T_{ref}), \tag{3.4}$$

with E_r the thermal energy content of the reservoir [J], ρ_b the bulk density of the reservoir [kg/m^3], c_b the bulk specific heat capacity of the reservoir [J/kg/K], V the volume of the reservoir [m^3], T_R is the characteristic reservoir temperature [K] and T_{ref} is the reference temperature [K], which is in this case the surface temperature.

The thermal energy content indicates the total amount of geothermal energy that is stored within the reservoir. However, not all of this energy can be produced, as a certain amount of energy will always remain in the subsurface. How much energy can be produced by a geothermal system will be described in the following section.

3.1.3. Thermal Energy available in a reservoir

To compute the amount of energy that can be extracted from a geothermal reservoir, a numerical simulation of the reservoir is used. During the production from a geothermal reservoir, cold water is injected and hot water is being extracted. This will result in a temperature drop within the reservoir.

For this study the reservoir is represented by a number of grid cells, during the simulation of the geothermal production process. The temperature within each cell for every time step during the production period is monitored. With this data, the thermal energy change of the reservoir can be determined using the following equation (Franco and Donatini, 2017):

$$\Delta E_i = \rho_{bi} \cdot c_{bi} \cdot V_i \cdot (T_i - T_{i,ini}), \tag{3.5}$$

with ΔE_i the time-integrated change in thermal energy content of cell i [J], ρ_{bi} the bulk density of the reservoir in cell i [kg/m^3], c_{bi} the bulk specific heat capacity of the reservoir in cell i [J/kg/K], V_i the volume of cell i [m^3], T_i is the time-integrated temperature in cell i [K] and $T_{i,ini}$ is initial (before production started) temperature of cell i [K]. The time-integrated thermal energy change of the whole reservoir ΔE, can be calculated by adding up all the ΔE_i for all reservoir cells. By calculating the change in energy content for every cell, the movement of the cold front can be examined.

It is also possible to compute the change in energy content of the reservoir for every time step. The equation to calculate this is very similar to Equation 3.4 and 3.5, and can be written as:

$$\Delta E_x = \rho_b \cdot c_b \cdot V \cdot (T_x - T_{x-1}), \tag{3.6}$$

with ΔE_x the change in thermal energy content of the reservoir between time step x and x-1 [J], T_x the temperature of the reservoir at time step x [K], and T_{x-1} the temperature of the reservoir at time step x-1 [K]. By calculating the energy content of the reservoir per timestep, we can accurately determine when thermal break-through occurs.

3.1.4. Produced Energy from the reservoir

The power output obtained from the of thermal energy produced from the geothermal reservoir is based on the temperature difference between the extracted and injected water. When a doublet system is installed, a heat exchanger extracts heat from the produced geothermal water. As a result, this water cools down. That cooled down water is then reinjected into the subsurface. The following equation provides a relation between the injected and the produced power as a function of the amount of produced water (Nick, 2017):

$$P = \rho_f \cdot c_f \cdot Q \cdot (T_{prod} - T_{inj}), \tag{3.7}$$

with P the power output [W], Q the volumetric production rate [m^3/s], T_{prod} the production temperature [K] and T_{inj} the injection temperature [K]. The power output gives an indication of how much the geothermal project yields in terms of energy demand.

The amount of heat that is produced, is however not equal to the decrease of the heat present in the reservoir. This is the result of thermal energy recharge, and that will be further discussed in the next section.

3.1.5. Thermal Recharge

A geothermal reservoir is not a closed system within the subsurface, there is interaction between the reservoir and its confining layers. Thermal energy can flow from the confining layers towards the reservoir and vice versa. Even without production there is a continuous flux through these layers.

During geothermal production, heat from the confining layers can flow towards the reservoir.

For example; there is a reservoir with an energy content of 10 PJ, and during 10 years of production it produced 1 PJ. One could expect that the energy content left in the reservoir is 9 PJ. However, during production 0.5 PJ of thermal energy has flowed from the confining layers towards the reservoir, due to the cooling of the reservoir. After 10 years of production, the reservoir has an energy content of 9.5 PJ even though 1 PJ has been produced, and the recharged thermal energy is 0.5 PJ.

In other words, the amount of thermal energy that is produced, will be higher than the change in thermal energy in the reservoir. The amount of heat that has flowed from the confining layers towards the reservoir is called recharged thermal energy. Thermal recharge occurs during production and also after production has been shut down. The amount of thermal energy that is recharged E_t during production, can be calculated using the following equation (Poulsen et al., 2015):

$$E_t = \Delta E + E_p, \tag{3.8}$$

with ΔE the time-integrated change in energy content of the reservoir [J] and E_p the time-integrated extracted energy from the production well [J]. The thermal recharged energy increases the energy content of the reservoir, and therefore enhances the lifetime of a geothermal project.

3.2. Heat Transport

The amount of thermal energy that is stored within the subsurface and how the amount of energy can change due to difference in temperature, is discussed in Section 3.1. This Section discusses the transport of heat, because change in thermal energy content is caused by the transport of heat.

The flow of heat is driven by a difference in temperature. Heat flow, $\mathbf{q_h}$, is represented by a vector, and it has a magnitude and a direction. Its magnitude indicates the amount of thermal energy crossing a surface and is expressed in $\mathrm{W/m^2}$.

The transfer of heat can occur in the subsurface either when it is in steady state or in transient state. In a steady state an equilibrium is attained and the temperature at any particular point in the system remains constant. When a system is in a transient state, there is no equilibrium and the temperature at a particular point changes in time.

For this study it is assumed that prior to geothermal production, the subsurface is in a steady state and when the production commences the system will be in a transient state. The following subsections discuss the thermal activities that occur during these states.

3.2.1. Conductive heat transport in the subsurface

When a system in the subsurface is in a steady state, there is a natural heat flow from the Earth's interior to the surface. This flow of heat consists of a convection and conduction component. The conductive heat flow, can be measured with Fourier's Law(Ferrell and Stahel, 2000). This law states that conductive heat flows from a high temperature to a low temperature, and that the amount of heat flow is dependent on the conductivity of the medium through which it is travelling:

$$q_h = -\lambda \nabla T, \tag{3.9}$$

where ∇T is the temperature gradient tensor, and λ is the thermal conductivity of the material[W/m/K].

For a subsurface that is in steady state, the heat flux has a vertical direction, from the interior of the Earth towards the surface. Hence, there is no temperature difference in the x & y direction which reduces ∇T to dT/dz. This vertical temperature difference is called the temperature gradient of the subsurface. The average thermal gradient in upper continental crust is between 25 ^{o}C and 30 ^{o}C/km (Fridleifsson et al., 2008). Throughout all the layers of the subsurface the heat flow $\mathbf{q_h}$ is constant. As a result, the temperature gradient does not have a constant value throughout the subsurface, but can vary with depth, due to the varying thermal conductivities of various lithologies.

The heat flux from the interior of the Earth to the surface is a constant flow of heat. Figure 3.2 shows a schematic representation of the a steady state system. The red arrows represent the constant heat flux through various layer of the subsurface.

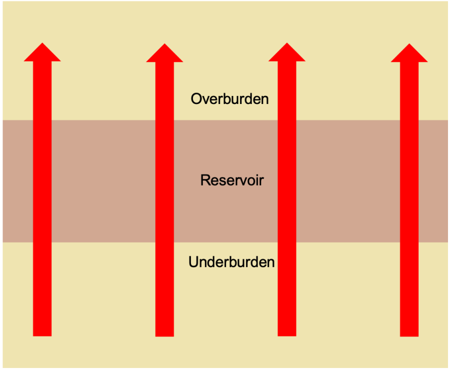


Figure 3.2: A schematic overview of a section of the subsurface of the Earth. The red arrows represent the constant heat flux from the interior of the Earth towards the subsurface.

3.2.2. Thermal Conductivity

The flow of heat is based on a difference in temperature. To what extent and in which way heat can flow through a material, is dependent on the thermal properties of that material. Thermal conductivity, λ [W/m/K], is a property of a material that is a measure to to what extent the material is capable of conducting heat for a given temperature gradient. It is the equivalent of permeability for fluid flow. During geothermal production this property plays an important role in the transfer of heat. The amount of heat that flows through a material from a high to a low temperature area, is proportional to the difference in temperature divided by the distance between the two places. Because thermal conductivity is based on conductive heat transfer, and heat conducts more easily through solids than through fluids, the thermal conductivity of a rock is higher than the thermal conductivity of the pore fluid (Chekhonin et al., 2012).

For a porous medium, the bulk heat conductivity is calculated in the following manner(Nick, 2017):

$$\lambda = \theta \lambda_f + (1 - \theta)\lambda_s, \tag{3.10}$$

where λ_f and λ_s are respectively the conductivity of the pore fluid and the matrix rock [W/m/K].

The ranges for thermal conductivity for different lithologies that can be found in literature is large (Chekhonin et al., 2012, Luijendijk, 2012, Poulsen et al., 2015, Willems and M. Nick, 2019). Figure 3.3 shows that the range of the thermal conductivity is measured on a logarithmic scale. Sandstone can have a thermal conductivity in the range of 0.5-7 W/m/K, and shale in the range of 0.6 - 5 W/m/K.

Section 4.2 and 4.3 describe the effect that thermal conductivity has on the geothermal production profile.

Anistropy

Often thermal conductivity in rocks exhibits anistropy. Temperature difference in various directions within the rock, experience different magnitudes of heat flow. Layering in rocks is the main cause for anistropy, and generally the thermal conductivity parallel to the layering is higher than the thermal conductivity perpendicular to the layers (Chekhonin et al., 2012). This is called anistropy.

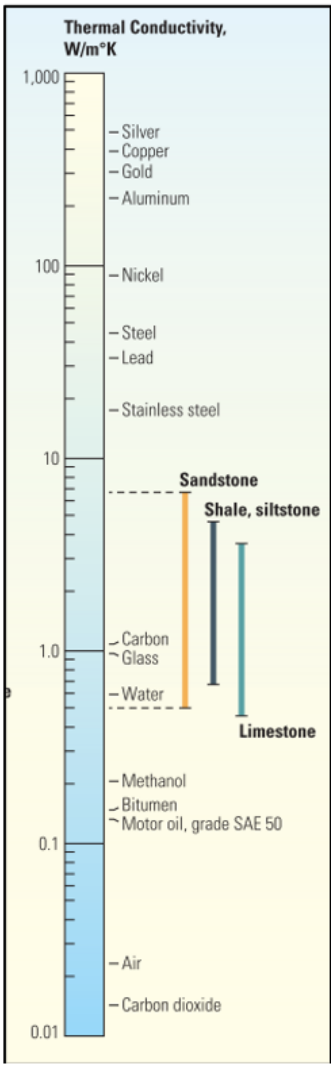


Figure 3.3: The range of thermal conductivity for different lithologies (Chekhonin et al., 2012).

3.2.3. Heat transport in the subsurface during geothermal production

The production from a geothermal reservoir causes a transient state in the subsurface. The extraction of hot water and injection of cold water results in a transient temperature distribution within the reservoir and its confining layers. Due to the difference in temperature a number of heat transport phenomena will occur.

Within the reservoir, the injected cold water will spread from the injection well to all directions. Near the producing well, the hot water will flow towards it. This hot water is coming from all directions. The pressure difference between the two wells will cause a flow from the injection well towards the producing well. Due to the temperature difference a cold temperature front will move from the injection towards the producing well. In this process, both convective and conductive heat flow occurs. Convective heat flow involves hot pore fluid moving towards the producing well. Conductive heat flow is controlled by internal heat of the matrix conducting heat towards the pores, and heating the pore fluid. Due to this internal heating of the pore fluid, the cold water front is delayed. The velocity at which this front travels is dependent on the retardation factor (Section Retardation).

The over- and underburden also play an important role in the heat transport, during the production from a reservoir. When the reservoir cools down due to injection of cold water, a temperature difference between the reservoir and the confining layers will arise. Presuming that the over- and underburden are not completely impermeable, convective heat transfer between the reservoir and over- and underburden will occur. Hot water from the confining layers will flow into the reservoir. Another heat transfer phenomenon that will occur is conduction of heat from the over- and underburden towards the reservoir. Dependent on the conductivity of the confining layers, and the amount of temperature difference, heat will be extracted from the over- and underburden and transferred to the reservoir. This phenomenon is called thermal recharge (Section 3.1.5).

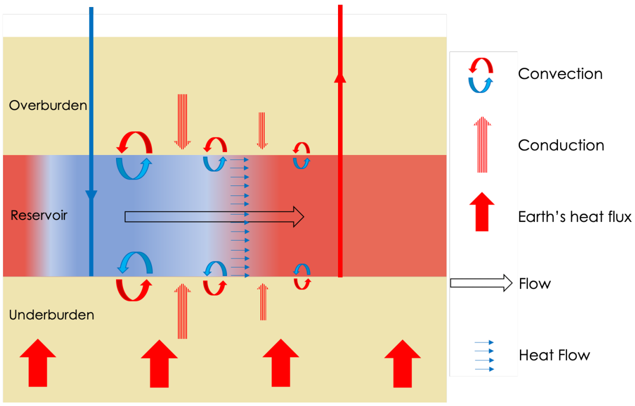


Figure 3.4: A schematic overview of a geothermal reservoir and the heat transport phenomena that occur during production. The blue and red lines represent respectively the injection and production well. The size of the convection and conduction arrow, is proportional to the amount of heat transfer.

For both the convective and conductive heat transfer it holds that the larger the temperature difference between the reservoir and the confining layers, the larger the heat flow. Figure 3.4 gives a schematic overview of the heat transport processes that occur during production from a geothermal reservoir. It indicates that in the parts of the reservoir where the cold front has spread, the heat flows in the form of conduction and convection, are larger than in the parts of the reservoir where the cold front has not spread yet.

Retardation

One of the effects of the injection of cold water in a geothermal reservoir, is the thermal retardation. Thermal retardation is the phenomenon that the thermal front is moving slower than the fluid causing the change in temperature. The retardation factor, R_t [-], can be determined using the following equation (Nick, 2017):

$$R_t = \frac{\rho_b c_b}{\theta \rho_f c_f}, \tag{3.11}$$

where θ is the porosity, ρ_b and ρ_f respectively the bulk density and pore fluid density[kg/m^3], c_b and c_f are the heat capacity of respectively the bulk and pore fluid [J/kg/K]

This phenomenon is important when determining when thermal break-through occurs. Because the heat is moving slower than the water, prior to a thermal breakthrough, a chemical breakthrough occurs.

3.3. Simulation Tool

This study uses SEAWAT to simulate the production from a geothermal reservoir. SEAWAT is a software program developed by USGS. It is a coupled version of MODFLOW and MT3DMS, which solve respectively the flow and transport equation. SEAWAT is designed to simulate three-dimensional, variable-density groundwater flow using a finite difference approximation (Langevin et al., 2007). The latest version of SEAWAT, SEAWAT_V4, additionally accommodates simultaneous solute and heat transport.

3.3.1. Physics and simulation of geothermal processes

This section presents some of the calculations that SEAWAT, MT3DMS and MODFLOW execute.

Solute Transport

MODFLOW simulates groundwater flow through porous media. The discharge that occurs is described by Darcy's law:

$$q = -K\nabla h, \tag{3.12}$$

with q the specific discharge vector [m/s]. K is the hydraulic conductivity in [m/s], h is the hydraulic head [m] and ∇ is the gradient vector in x, y, z direction [-].
The hydraulic conductivity K can be calculated using the following equation:

$$K = \frac{k\rho_f g}{\mu}, \tag{3.13}$$

with k the permeability in the same direction as the hydraulic conductivity [m^2], ρ_f the fluid density [kg/m^3], g the gravitational constant [m/s^2] and μ the viscosity [kg/m/s]. Because of the fact that the hydraulic conductivity is defined by density and viscosity, it is temperature dependent.

Originally, SEAWAT and MT3DMS are not intended to calculate heat transport. However, by treating heat as a solute species, transport of heat can be modeled.
MT3DMS uses Equation 3.14 to calculate the solute transport (Langevin et al., 2007).

$$\left(1 + \frac{\rho_b K_d^k}{\theta}\right)\frac{\partial\left(\theta C^k\right)}{\partial t} = \nabla\cdot\left[\theta\left(D_{diff}^k + \alpha\frac{q}{\theta}\right)\cdot\nabla C^k\right] - \nabla\cdot\left(qC^k\right) - q_s' C_s^k, \tag{3.14}$$

with ρ_b the bulk density [kg/m^3], K_d^k the distribution factor of solute (often this is the salt content in the water) k [m^3/kg], C^k is the concentration of solute k [kg/m^3], D_{diff}^k the molecular diffusion coefficient of solute k [m^2/s], α is the dispersivity tensor [m] and $\alpha\frac{q}{\theta}$ is the dispersion. C_s^k is the concentration of solute k in the source [kg/m^3].

Heat Transport

Equation 3.14 is mathematically similar to the heat transport equation (Langevin et al., 2007):

$$\left(\frac{\rho_b c_b}{\theta c_f \rho_f}\right)\frac{\partial(\theta T)}{\partial t} = \nabla\left[\theta\left(\frac{\lambda_b}{\theta c_f \rho_f} + \alpha\frac{q}{\theta}\right)\nabla T\right] - \nabla(qT) - q_s' T_s, \tag{3.15}$$

where T_s the temperature in the source [K]. Due to this similarity, SEAWAT is able to to calculate the thermal processes in the subsurface.
Equation 3.15 includes the processes of retardation, conduction, dispersion and advection to calculate the heat transport.

Retardation of the thermal front is expressed in the term $\left(\frac{\rho_b c_b}{\theta c_f \rho_f}\right)$. This process is comparable with the distribution of the solute in 3.14. To account for this process, the distribution coefficient of solute K_d^k is replaced by the thermal distribution factor K_d [m^3/kg]. The thermal distribution factor can be calculated using the following equation (Langevin et al., 2007):

$$K_d = \frac{c_s}{\rho_f c_f} \tag{3.16}$$

Conduction of heat is the component in Equation 3.15 that is expressed with the term $\frac{\lambda_b}{\theta c_f \rho_f}$. Thermal conduction is mathematically similar to molecular diffusion. Section 3.2.1 describes that conductive heat flux is directly proportional to a temperature gradient, expressed by Fourier's Law (see Equation 3.9). In mass transfer, diffusional mass flux is directly proportional to its concentration gradient by Fick's Law (Ferrell and Stahel, 2000):

$$J = -D_{diff}^k \nabla\varphi, \tag{3.17}$$

with J the Diffusion flux, D^k_{diff} the molecular diffusion coefficient of solute and $\nabla\varphi$ concentration gradient. In both Fourier's and Fick's Law, transport occurs in response to a gradient. Therefore, the diffusion coefficient of solute in Equation 3.14 is replaced by the thermal diffusivity term D_H [m^2/s] in Equation 3.15.
Thermal diffusivity is used to calculate the conductive heat transport with a diffusion equation. Thermal diffusivity describes the rate of temperature spread through a material (Ferrell and Stahel, 2000). Thermal diffusivity is determined by a combination of thermal conductivity and volumetric heat capacity. When more heat is flowing into a unit volume than flowing out of it, the temperature will rise. The rate of the heat flow is determined by the thermal conductivity. The temperature increase of the material is dependent on the heat capacity (Chekhonin et al., 2012).

Figure 3.5 illustrates schematically what thermal diffusivity is.

The thermal diffusivity term can be calculated using the following equation (Langevin et al., 2007):

$$D_H = \frac{\lambda_{bulk}}{\theta \rho_f c_f} \tag{3.18}$$

Dispersion is the process where local variations in flow velocity result in the mixing of the fluid. In Equation 3.15 the dispersion term D is given by:

$$D = \alpha \frac{q}{\theta}, \tag{3.19}$$

where α [m] is the dispersion tensor. Moving further from the injection well, the flow velocity will decrease. As a result the dispersion will decrease as well.

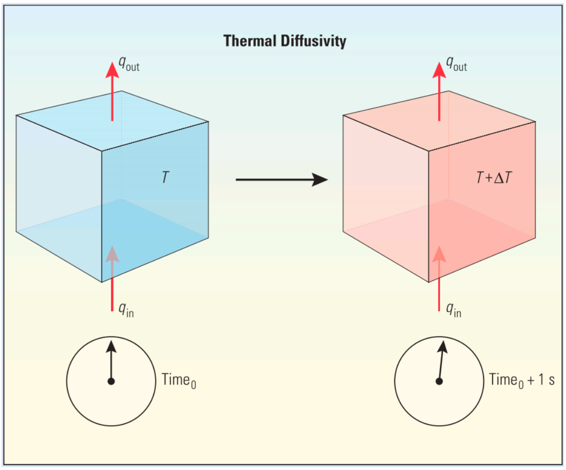


Figure 3.5: Thermal Diffusivity, the ratio between thermal conductivity and volumetric heat capacity. After an amount of time (1 sec) the box model is heated ∇T degrees due to a difference in q$_{in}$ and q$_{out}$, which are respectively the heat flow in and heat flow out. (Chekhonin et al., 2012)

Advection Heat transport due to advection, is in Equation 3.15 represented by qT. Advection describes the heat transport in porous media by the flow of ground water. Both the dispersion and advection term in Equation 3.15 are mathematically similar to the terms in Equation 3.14.

Variable Density

SEAWAT solves the variable-density ground-water-flow equation (Equation 3.20) for each timestep to calculate the heat and flow (Langevin et al., 2007).

$$\nabla\left[\rho\frac{\mu_0}{\mu}K_0\left(\nabla h_0 + \frac{\rho-\rho_0}{\rho_0}\nabla z\right)\right] = \rho S_{s,0}\frac{\partial h_0}{\partial t} + \theta\frac{\partial \rho}{\partial C}\frac{\partial C}{\partial t} - \rho_s q_s' \tag{3.20}$$

In Equation 3.20 ρ_0 is the fluid density at reference concentration and temperature [kg/m^3], ρ_s is the density of the source and sink [kg/m^3]. μ_0 is the dynamic viscosity at reference concentration and temperature [kg/m/s]. K_0 is the hydraulic conductivity tensor of material saturated with reference fluid [m/s]. h_0 is the hydraulic head measured in terms of the reference fluid of a specified concentration and temperature [m]. $S_{s,0}$ is the specific storage, defined as the volume of water released from storage per unit volume per unit decline of h_0 [m^1]. t is time, C is salt concentration [kg/m^3] and q_s' is a source or sink of fluid with density ρ_s.

The density of a fluid is temperature dependent. The standard version of SEAWATv4, uses a linear relationship between these two. However, a recent study (Marif, 2019) showed, that beyond a certain temperature, the temperature-density relationship does not act linearly. Equation 3.21 shows this relationship;

$$\rho(T) = 1000 - 2.9758 \cdot 10^{-3}(T + 15.31)^2. \tag{3.21}$$

To account for this, a new version of SEAWAT was developed SEAWATv4nonlin, that takes this non-linear relationship into account.

3.4. Model Setup

The SEAWAT software is used to set-up a model that is a three-dimensional representation of a geothermal system. We started off by constructing a Base Case. This Bases Case serves as a reference for other cases in which the parameters have been varied to test the sensitivity of the model to that particular parameter.

This section discusses the model input and setup. Table 3.1 gives a schematic overview of all the input parameters.

Parameter	***Value***		
Dimensions			
Reservoir thickness	50 m	100 m	200 m
Model cells (z,x,y)	41,100,100	46,100,100	56,100,100
Depth top model	1665 m	1640 m	1590 m
Depth top reservoir	2475 m	2450 m	2400 m
Depth bottom reservoir	2525 m	2550 m	2600 m
Cell size (reservoir and surrounding)	10*40*40 m		
Over- and under burden thickness	800 m		
Well data			
Injector well (x,y)	50,35		
Producer well (x,y)	50,65		
Well distance	1200 m		
Injection temperature ^{o}C	35 ^{o}C		
Injection rate	150 m^3/hr		
Temperature Data			
Surface temperature	10.35 ^{o}C		
Temperature gradient confining layers	32.5 ^{o}C/km		
Temperature gradients reservoir	21.7 ^{o}C/km		
Initial average reservoir temperature	90.25 ^{o}C		
Surface pressure	1.03 Bar		
Pressure gradient	10 Mpa/km		
Rock Properties			
Density	2650 kg/m^3		
Heat capacity	800 J/kg/K		
Reservoir			
Heat conductivity	3 W/m/K		
Porosity	20 %		
Permeability	200 mD		
kv/kh	0.1		
Confining layers			
Heat conductivity	2 W/m/K		
Porosity	7 %		
Permeability	0.01 mD		
kv/kh	0.1		
Fluid Properties			
Density	1085 kg/m^3		
Salinity	0.12 kg/kg		
Viscosity	6.8 *10^{-4} kg/m*s		
Heat capacity	3561 J/kg/K		
Heat conductivity	0.73 W/m/K		

Table 3.1: Base Case input parameters

3.4.1. Boundary Conditions

For different experiments per case, the reservoir has a thickness of 50, 100 and 200 meters. The middle of the geothermal reservoir lies at a depth of 2500m confined by an over- and underburden of more than 800m thick. Horizontally the model has a size of 6.2 km x 6.2 km. The outer cells of the model are all conditioned with a constant temperature and head boundary. A constant head boundary provides an inexhaustible supply or sink of water to and from the model.

The heat flow from the center of the Earth towards the subsurface, q_h, is set equal to 65 mW/m^2

(Davies and Davies, 2010). The temperature gradient in the model depends on the heat flow and the thermal conductivity of the formation (Equation 3.9). Due to the fact that the over- and underburden have a different thermal conductivity than the reservoir, the temperature gradient throughout the model is not constant. The temperature gradient in the over- and underburden and the reservoir is respectively 32.5 ^{o}C/km and 21.67 ^{o}C/km. With a surface temperature of 10.1 ^{o}C, this corresponds to an average initial reservoir temperature of 90.1 ^{o}C.

3.4.2. Production Parameters

In the Base Case one doublet is active. The injection and production well are aligned in the middle of the reservoir 1200 m apart. The wells have a vertical orientation. The injection rate is 150 m^3/hr, with a temperature of 35^{o}C. The production rate is similar to the injection rate. Both the injection and producing well are perforated along the whole length of the reservoir. The simulation runs for 300 years, with a constant production rate throughout the entire simulation. The wells are perforated along the entire thickness of the reservoir. Appendix B discusses the effect of the perforation strategy and why we chose to perforate the well along the entire thickness of the reservoir.

3.4.3. Rock Properties

From top to bottom the model is vertically divided into the overburden, the reservoir and the underburden. The rock properties of the reservoir are similar to the properties of sandstone, the rock properties of the over- and underburden are similar to the properties of shale.

The density of the matrix in both the reservoir and over- and underburden is 2650 kg/m^3, which is representative for both sandstone and shale. The porosity of the reservoir is set at 20% with a permeability of 200 mD, and the porosity of the over- and underburden is 7% with a permeability of 0.01 mD. The kv/kh ratio is 0.1 for the whole model.

The heat capacity of the matrix of the whole model is 800 J/kg/^{o}C. The possible range for the thermal conductivity of both sandstone and shale is large, as discussed in Section 3.2.2 and shown in Figure 3.3. For the thermal conductivity of the Base Case, an average of this range is taken, for the reservoir a thermal conductivity of 3 W/m/^{o}C, which is representative for a sandstone. The thermal conductivity of the over- and underburden is 2 W/m/^{o}C, which is representative for a shale. These differences in thermal conductivity cause a change in temperature gradient throughout the whole model.

3.4.4. Hydraulic Properties

The pore fluid in the model is water. The pore fluid has a salinity of 12%. The reference density and viscosity of the pore fluid are respectively 1061.5 kg/m^3 and 0.00054 kg/m/s.

The water at reservoir conditions has a thermal conductivity of 0.74 J/s/m/^{o}C and the heat capacity is 3464 J/kg/^{o}C (International Association for the Properties of Water and Steam, 1994).

3.4.5. Discretization

To provide stable and accurate results with a groundwater flow and heat-transport model, it is important to have a correct spatial and temporal discretization.

Spatial discretization, i.e. the grid size, should be consistent with the dispersivity parameters (Reyes et al., 2013). The values for the longitudinal dispersivity α_L and transverse dispersivity α_T, are respectively 10m and 1m.

The ground water flow, from the injection well to the producing well, travels in the y-direction.

Using the following equation to calculate the Peclet number, the correct grid spacing can be determined:

$$Pe = \frac{\Delta x}{\alpha_L}, \tag{3.22}$$

with Pe the Peclet number, Δx the grid spacing in the direction of the flow and α_L the longitudinal dispersivity tensor. Numerical stability can be expected with a Peclet number of 4, but is ensured with a Peclet number smaller than 2 (Poulsen et al., 2015).

Longitudinal dispersivity is used to represent the local variations in the velocity field of a ground water solute in the direction of fluid flow (Neuman, 2006). Dispersion perpendicular to the flow direction is represented by horizontal and vertical transverse dispersivity α_{Th} and α_{Tv} (Delgado, 2007). The longitudinal dispersivity in this model is 10m. The transverse dispersivity tensors are represented by the ratio of the transverse dispersivity to the longitudinal dispersivity. For the horizontal and vertical transverse dispersivity this ratio is respectively 0.1 and 0.01.

In addition to the dispersivity tensor, a grid size that is consistent with the dispersivity is important. In areas where accurate results are required, a finer mesh is recommended. A finer mesh o the grid means that more cell should be used, as a result the computational time per simulation increases.

In the model that is used for this study, the cells near the wells have a size of 40m by 40m in the x and y direction. To minimize the effect of the boundary conditions, without increasing the computing time of the simulation, the cells near the boundary of the model, have a size of 100m by 100m. The vertical cell size is 10m within the reservoir and the vertical 100m surrounding the reservoir. Using Equation 3.22 and the given cell sizes to calculate, a Peclet number of 4 is obtained for the model that is used for this study.

Literature argues that a Peclet number smaller than 2 should be used (Reyes et al., 2013). Because the simulation conducted for this research work with a Peclet number of 4, the stability of the model is checked. To check whether the model with the given grid size and Pe=4, is numerical stable, a simulation was executed with the size of all the cells in the model half of the grid size of the Base Case. Appendix A, Figure A.1 provides the results of this test. The results of the two simulations are almost identical, therefore we decided to work with the larger grid size to decrease the computational time per simulation.

Not only the discretization of the cells in the reservoir will have effect on the result of the simulations of this model, the over- and underburden play an important role as well. To reduce the computational time per simulation, it might be tempting to to minimize the amount of cells and maximize the grid size in the confining layers. Appendix A, Figure A.2 shows what happens to the production temperature and the recharge ratio, when over- and underburden are represented by two vertical cells each. Due to the large cell sizes in the over- and underburden, the simulations are not accurate. To ensure that the simulations are as representative as possible, but still trying to minimize the computational time, the vertical cell size in the over- and underburden are varied. The 10 vertical cells adjacent to the reservoir have the same vertical thickness as the reservoir. The outer 7 cells have a thickness of 100 meters, to create enough distance between the reservoir and the boundary to minimize the effect of the boundary conditions. The boundary cell has a thickness of 10 meters, again to ensure minimal influence of the boundary conditions. Figure 3.6 shows the grid size of the Base Case. It displays a top view of the model and a side view of the model.

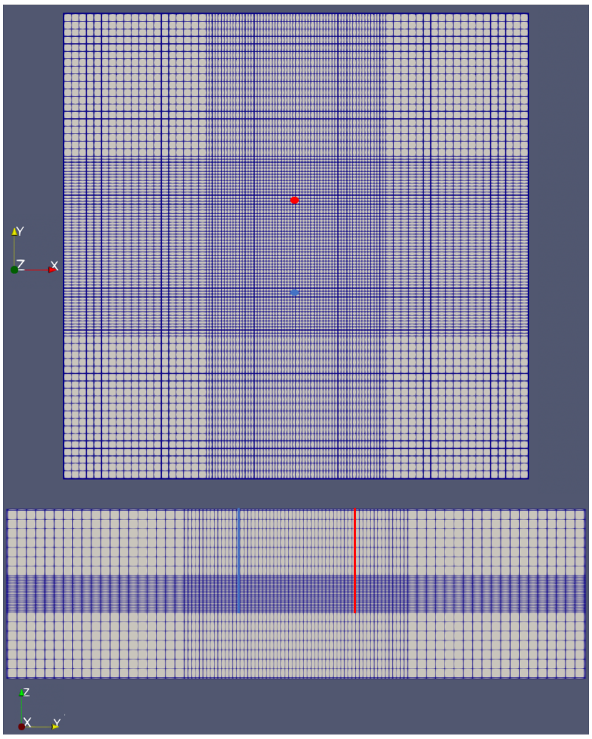


Figure 3.6: The grid size of the model. The top image is a top view of the reservoir. The bottom image is a side view on the model. The blue dot and line represent the injection well. The red dot and line represent the production well.

All the input values of the Base Case are summarized in Table 3.1.

In addition to the spatial discretization, there is also a temporal discretization. To determine the temporal discretization that is used in the simulations of SEAWAT, the following equation is used

(Guo and Langevin, 2002):

$$\Delta t \leq \frac{0.5}{\frac{D_{xx}}{\Delta x^2}+\frac{D_{yy}}{\Delta y^2}+\frac{D_{zz}}{\Delta z^2}}, \tag{3.23}$$

with Δt the length of a timestep and Δx Δy Δx the dimensions of the model cell. D_{xx}, D_{yy} and D_{zz} are respectively the dispersion in the x, y and z direction. In eq. 3.14 and 3.15 this is dimensionless expressed by $\alpha\frac{q}{\theta}$.

3.5. Experiments

Multiple experiments are conducted, where one parameter was altered compared to the Base Case, to examine their effect. First, the effect is of a number of geological uncertainties were examined. Subsequently, the effect of the production parameters on the production profile were examined. The geological uncertainties consist of reservoir thickness, thermal conductivity and permeability. The production parameters are production rate and well spacing.

The first geological uncertainty, and its effect on the production profile that is examined, is the reservoir thickness. Case 1 test reservoirs with thicknesses of 50, 100 and 200 meter, representative for geothermal reservoirs in the Netherlands (TNO, 2018). (Section 4.1)

The thermal conductivity of the matrix of both the reservoir and the over- and underburden is the second geological parameter that is tested. The range of possible thermal conductivities for sandstone and shale is large (Chekhonin et al., 2012) (Figure 3.3).

Case 2 test the effect of the thermal conductivity of the reservoir. The Base Case is set at 3 W/m/K, which is representative for a sandstone. The tests for a lower or higher case have a thermal conductivity of respectively 1.5 and 5 W/m/K, which is a representative range for the thermal conductivity of sandstone (Chekhonin et al., 2012) (Section 4.2).

Case 3 tests the thermal conductivity of the confining layers. The Base Case has a thermal conductivity of 2 W/m/K, the lower and higher cases have a thermal conductivity of respectively 0.8 and 3.5 W/m/K, which is within the range for the thermal conductivity of shale (Chekhonin et al., 2012) (Section 4.3). These tests are conducted for a reservoir of both 50 and 200 meters thick.

Case 4 describes the last geological uncertainty that is tested, the permeability of the over- and underburden. In the Base Case the confining layers have a permeability of 0.01 mD., the tests examine the effect when the permeability is increases to 10 mD and 100 mD. The models for which the effect of a change in the permeability is tested have a reservoir thickness of 50, 100 and 200 meters (Section 4.4).

The second part of the experiments examines the effect of the production parameters, in order to find a sustainable production optimisation.

The production rate is the first production parameter that will be examined. Case 5 includes two types of tests. First, we tested the effect when the production rate increases proportionally with the reservoir thickness. A reservoir of 50, 100 and 200 meters thick have a production rate of respectively 150, 300 and 600 m^3/hr, to illustrate the effect that a proportional production rate to reservoir thickness has. The second type of tests, examines the effect of an increase in production rate for a reservoir of 200 meters. For these experiments we examines the effect of a production rate of 150, 250, 400 and 600 m^3/hr (Section 4.7).

Case 6 describes the second production parameter we tested, the effect of well spacing. In the Base Case the distance between the injection and producing well is 1200 meters. The lower and the higher cases have a well distance of respectively 1000 and 1500 meters.

This effect is tested for a reservoir of both 50 and 200 meters thick (Section 4.8).

For every experiment, only one parameter is altered, compared to the Base Case.

3.5.1. Assessment framework

For this study we have monitored the following outputs from the simulation; The well temperature and the recharge ratio. These outputs together form the production profile.

The production temperature consists of the average temperature of the vertically stacked cells that form the production well.

The recharge ratio depends on the thermal recharge (Equation 3.8). To determine the recharge ratio, the thermal recharge, i.e. the amount of energy that has flowed from the over- and underburden towards the reservoir, is divided by the amount of produced energy:

$$recharge\,ratio = \frac{thermal\,recharge}{produced\,energy} = \frac{E_t}{E_p}, \tag{3.24}$$

with E_t the thermal recharge (Equation 3.8) and $E_p$the amount of produced energy (Equation 3.7). For all the tests of all 6 different cases the well temperature and recharge ratio are plotted for the 300 simulated years. These are all provided in Appendix C.

For some experiments we plotted the thermal recharge or well temperature against the energy extracted per representative reservoir volume. The following equation shows how to calculate the representative volume:

$$volume = thickness\,of\,the\,reservoir\ \cdot\ well\,spacing\ \cdot\ width\,of\,1\,cell. \tag{3.25}$$

In addition to the well temperature and the recharge ratio plots, the following four output values after 300 years of production are noted:

- The well temperature difference.
- The thermal recharge.
- The thermal break-though time.
- The temperature decrease percentage.
- The deviation from the Base Case.

First of all, the well temperature difference is the difference in well temperature after 300 years of production, ΔT [^{o}C]. This is determined by subtracting the average well temperature after 300 years from the initial average reservoir temperature.
Secondly, is the thermal recharge, this includes both the recharge ratio [%] and the thermal recharge E_t in PJ [PJ = 10^{15}J].
Thirdly, is the thermal break-through time (TBT). This indicates after how many years of production the well temperature starts to decline. The threshold for the break-through time is when the average well temperature has declined by 0.5^{o}C, compared to the initial average well temperature.
The fourth output gives a time indication for the temperature decrease percentage (TDP) of 25%, this the time it takes for the well temperature to decrease by 25% of the difference between the injection and the initial temperature. For the Base Case the TDP is determined as follows: The initial reservoir temperature is 90^{o}C and the injection temperature is 35^{o}C. A well temperature decrease of 25% of the difference between initial and injection temperature, results in a well temperature of 76.25 ^{o}C. The result presented indicates the time [years] that the produced well temperature is above a TDP of 25%.
Fifthly, is the deviation of the results to the results of the Base Case. This is calculated for for both the well temperature decline (ΔT) and thermal recharge ratio.

4

Results and Analyses

This chapter presents the results of the six cases tested for this research.
For every case the sensitivity of the model to the relevant parameters is tested. The starting point of every test is the Base Case, Table 3.1 presents the input values for the Base Case. For every case the production rate and recharge ratio are monitored. These results are compared to the results of the Base Case to determine the sensitivity of the production process to these parameters.
The parameters that are tested, can be divided into two categories, geological uncertainties and production control. For every parameter the effect on the production process is examined. The first part of this chapter, Section A, contains the results and analyses of the experiments examining the effect of geological uncertainties. The second part of this chapter, Section B, presents the results and analyses of the experiments examining the production parameters.

A. Geological Uncertainties

This part of Chapter 4 presents what the effects are of geological uncertainties on the production process. The following geological uncertainties are examined

- Case 1: The reservoir thickness (4.1)
- Case 2: The thermal conductivity of the reservoir (4.2)
- Case 3: The thermal conductivity of the confining layers (4.3)
- Case 4: The permeability of the confining layers (4.4)

Every section consists of two subsections. The first subsection presents the results of the sensitivity study of the geological uncertainties on the production process. The second subsection contains an analysis of the effect of the parameter. Section 4.5 discusses the overall effect that the confining layers have on the production profile. Section4.6 summarizes what the effect are of the geological uncertainties on the development of a geothermal system.

4.1. Case 1: Reservoir thickness

This case tests the effect of the reservoir thickness on the production profile. The tested reservoir thicknesses are 50 meter, 100 meter and 200 meter. The reservoir model consists of respectively 5, 10 and 20 vertical cells. The over- and underburden remain the same thickness for all three cases. This section present and analyzes the results of these experiments.

4.1.1. Results

Figure 4.1 displays the temperature in the production well and the recharge ratio. Table 4.1 summarizes the results of 300 years of production for reservoirs with a thickness of 50, 100 and 200 meters.
These results show that with increasing thickness the temperature decline in the production well decreases. Thermal recharge can be measured as a ratio, i.e. relative to the total extracted energy, or as an absolute value. The recharge ratio for a reservoir with a thickness of 200 meters is less than half of the recharge ratio for a reservoir that is 50 meters thick. The absolute amount of thermal recharge for a reservoir with a thickness of 200 meters is a little more than half of the thermal recharge for a reservoir that is 50 meters thick. The thermal break-through increases with increasing thickness of

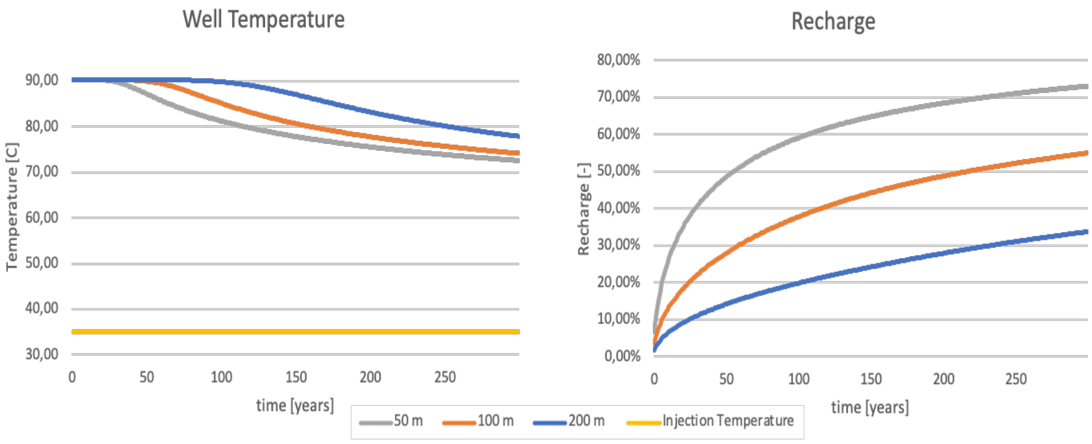


Figure 4.1: The sensitivity of the production temperature and recharge ratio to change in reservoir thickness, simulated over a period of 300 years. The left figure shows the production temperature. The figure on the left shows the recharge to the reservoir during production. This indicates the amount of energy, in the form of heat, that flows to the reservoir from the confining layers during production. The blue, orange and grey lines represent respectively reservoirs with a thickness of 200, 100 and 50 meter.

the reservoir. When thermal break-through occurs, the temperature in the production wells drops. As a result, less energy can be produced from this well.

To examine what the effect is of a change in reservoir thickness to the production process, the results of the reservoirs with a thickness of 100 and 200 meters are compared to the results of the reservoir with a thickness of 50 meters.

	Delta T	**Recharge**		**TBT**	**TDP**	**Deviation**	
		%	**PJ**	**-**	**-**	**Temperature**	**Recharge**
50 m	17.7	73.0	49.0	32	184	-	-
100 m	16.1	54.9	39.2	45	263	-9%	-25%
200 m	12.3	33.7	26.1	105	>300	-30%	-54%

Table 4.1: Results for the study on the sensitivity of the production process to reservoir thickness, after 300 years of production, with ΔT the decline in well temperature. The third and fourth columns give respectively the recharge ratio and the absolute thermal recharge in petajoule (10^{15}J). The fifth column displays the Thermal Break-Through in the production well in years. It gives an indication when the well temperature has dropped 1°C compared to the initial temperature. The sixth column displays the Temperature Decrease Percentage of 25%. It gives an indication when the temperature drop in the production well is 25% of the difference between the initial temperature and the injection temperature. The deviation is the case compared to the Base Case, a reservoir with a thickness of 50 meters.

Interpretation

The well temperature decline of a reservoir of 200 meters decreases almost one third compared to a reservoir of 50 meters thick. With an increasing thickness, the volume of the reservoir will increase. Therefore, it is intuitive that more heat can be produced from a larger reservoir. However, with a reservoir thickness that is four times larger, the thermal break-through does not take four times the amount of time. This could be due to the fact that with a thicker reservoir, the recharge ratio decreases. The recharge ratio of the reservoir with a thickness of 200 meters (33.7%) is less than half of the ratio of a reservoir of 50 meters (73%).

The thermal energy that causes the recharge comes from the over- and underburden. With an increasing thickness, the influence of the over- and underburden decreases. Therefore, the thermal recharge and recharge ratio decrease with a thicker reservoir.

These results show that the well temperature and recharge ratio are very sensitive to the reservoir thickness. To correctly study the effects of the other parameters, the results are compared for cases with different reservoir thicknesses. These three models with different reservoir thicknesses are considered to be the Base Cases. Table 3.1 presents the input values for these Base Cases.

4.1.2. Effect of Reservoir Thickness

The thickness of the reservoir is the geological parameter that has the largest effect on the production profile. With an increase in reservoir thickness and thus reservoir volume, the total thermal energy content in the reservoir will increase (Equation 3.4). Naturally with a larger energy content, more heat can be produced. Therefore, the well temperature decline is smallest for the thickest reservoir.

However, this does not necessarily mean that the thicker the reservoir, the more efficient the heat content is used. Recharge plays an important role in the production profile of a geothermal project. When energy is recharged towards the reservoir, the energy content in the reservoir will remain higher and this has a positive effect on the well temperature progression.

With the same production rate, the well temperature drops faster in a thinner reservoir, (Figure 4.1) due to its smaller energy content. This will result in a larger temperature difference between the reservoir and the over- and underburden. With a larger difference in temperature, the heat flow from the confining layers to the reservoir will increase, thus a larger recharge ratio compared to a thicker reservoir. This effect reduces the well temperature decline.

When contemplating the recharge ratio, a thinner reservoir may be favourable for a faster recharge. The recharge ratio increases with approximately 20% every time the reservoir thickness is halved.

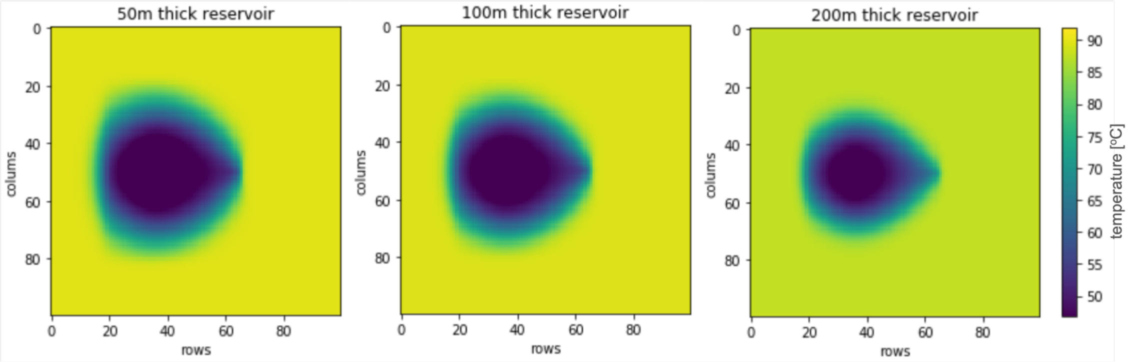


Figure 4.2: The temperature in the cell layer directly on top of the reservoir after 300 years of production. The area where temperature change occurs is 6.47 km², 5.57 km², and 4.16 km² for a reservoir with a thickness of respectively 50, 100, and 200 meters.

The increase in recharge ratio is explained using Figure 4.2. When recharge occurs, heat flows from the over- and underburden towards the reservoir. Because heat is extracted, the over- and underburden will cool down. The larger the area in the confining layers is, that is affected by this cooling down, the larger the thermal recharge is.

Figure 4.2 displays the temperature in the layer directly on top of the reservoir. Because all the heat from the over- burden travels trough this layer, it is representative for all the heat extraction from all confining layers.

Figure 4.2 shows that the thinner the reservoir, the larger the affected area is. The area where a temperature change of more than 0.5^oC occurs, after 300 years of production, is 6.47km^2, 5.57km^2, and 4.16 km^2 for a reservoir of respectively 50, 100 and 200 meters thick. In addition to this effect, the degree of temperature decrease is also larger for a thinner reservoir.

Looking at the results shown in Figure 4.2 the conclusion can be drawn that, the larger the area at the boundary between the reservoir and the over- and underburden where a decrease of temperature occurs, the larger the amount of recharge will be. The results shown in Figure 4.3 emphasize this conclusion. Figure 4.3 shows the well temperature against the produced energy per representative volume (Equation 3.25). The results show that when the same amount of energy is produced per representative volume, the well temperature in a thinner reservoir is higher.

Considering these results, the following conclusion is drawn. In a thinner reservoir more thermal recharge will occur. This results in a lower well temperature drop for the same amount of energy produced per volume, and enhances the sustainable use of the geothermal system.

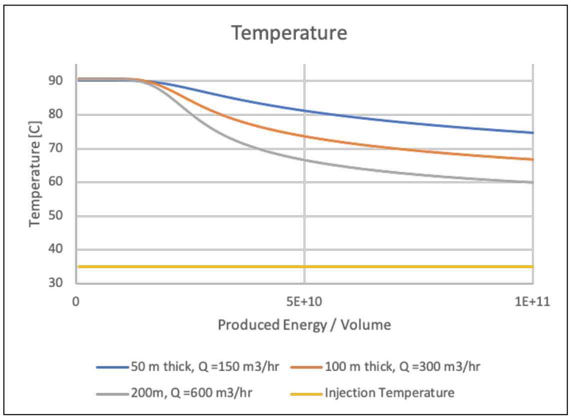


Figure 4.3: The well temperature against energy produced per volume for reservoirs of 50, 100 and 200 meters thick.

Another aspect from Figure 4.3 that is important to mention, is the well temperature appears to approach an asymptote. If the well temperature exhibits asymptotic behaviour, the production process might reach a steady state. Section 6.4 of the Discussion Chapter will elaborate further on this.

It is noted that, to properly compare the results, there should also be experiments where the production rate proportionally increases with the thickness of the reservoir. Case 5, in Section 4.7.2 discusses this.

4.2. Case 2: Thermal conductivity of the reservoir

Case 2 tests the second geological uncertainty, the thermal conductivity of the reservoir. This section presents the results of the effect of a change in the thermal conductivity of the reservoir.

4.2.1. Results

These tests examine the sensitivity of the production process to difference in the thermal conductivity of the reservoir rock λ_{rs}. The Base Case is used as a reference with a thermal conductivity of the reservoir matrix of 3 W/m/K. This section presents the results of two scenarios, with a thermal conductivity of 1.5 W/m/K and 5 W/m/K for the reservoir rock. The thermal conductivity of the over- and underburden rock is kept constant at λ_{cs} = 2 [W/m/K].
Table 4.2 summarizes the results of the scenarios for a reservoir with a thickness of both 50 meter and 200 meter. Appendix C.1 provides the corresponding graphs.

		Delta T	**Recharge**		**TBT**	**TDP**	**Deviation**	
	λ_{rs}		**%**	**PJ**			**Temperature**	**Recharge**
50 m	**1.5 W/m/K**	17.5	72.5	46.8	32	180	1%	-1%
	3 W/m/K	17.7	73.0	49.0	32	184	-	-
	5 W/m/K	17.0	73.7	48.0	34	208	-4%	1%
200 m	**1.5 W/m/K**	12.8	30.6	22.7	104	>300	4%	-9%
	3 W/m/K	12.3	33.7	26.1	105	>300	-	-
	5 W/m/K	11.1	36.7	26.9	107	>300	-10%	9%

Table 4.2: Results for the study on the sensitivity of the production process to the thermal conductivity of the reservoir rock, after 300 years of production. Explanation as in Table 4.1. The simulation where λ_{rs} = 3 W/m/K is considered to be the Base Case.

Independent to the reservoir thickness, the well temperature decline decreases with a larger thermal conductivity. Both the thermal recharge and the recharge ratio increase when the thermal conductivity increases. Also the thermal break-through is later with a larger thermal conductivity.
For a reservoir with a thickness of 200 meters the effects of the thermal conductivity changes are larger than for a reservoir with a thickness of 50 meters.

Interpretation

With a larger thermal conductivity in the reservoir, it is possible to produce water without a temperature decline for a longer period. With a higher thermal conductivity heat can travel faster through the material. Heat from the entire reservoir flows more easily to the production well. This results in the fact that more heat has the ability to flow to the production well in the same amount of time. As a result, a larger area surrounding the well is affected by the production.

With a larger spread of temperature change, the area that is in contact with the confining layers and experiences a change in temperature is also larger. Therefore, more recharge can occur, because this is driven by a temperature change between the reservoir and the confining layers. That explains why more thermal recharge occurs, with a higher thermal conductivity of the reservoir rock.
Section 4.3.2 discusses the effects of the thermal conductivity of the reservoir, in combination with the effects of the thermal conductivity of the confining layers.

4.3. Case 3: Thermal conductivity of the confining layers

Case 3 evaluates the third geological uncertainty,the thermal conductivity of the confining layers. This section analyzes the results and the effect of the thermal conductivity.

4.3.1. Results

These tests examine the effect of a change in thermal conductivity of the matrix of the confining layers (λ_{cs}). The Base Case has a thermal conductivity of 2 W/m/K for the matrix of the confining layers. This section presents the results of two scenarios where the thermal conductivity of the confining layers is 0.8 W/m/K and 3.5 W/m/K. The thermal conductivity of the reservoir rock is kept constant at λ_{cs} = 3 W/m/K. The effect of this parameter is reviewed for a reservoir with a thickness of 50 and 200 meters.

Table 4.3 summarizes the results of the different scenarios. Appendix C.2.1 provides the corresponding graphs.

	λ_{cs}	**Delta T**	**Recharge** %	**Recharge** PJ	**TBT**	**TDP**	**Deviation** Temperature	**Deviation** Recharge
50 m	**0.8 W/m/K**	21.8	64.3	41.3	29	121	23%	-12%
	2 W/m/K	17.7	73.0	49.0	32	184	-	-
	3.5 W/m/K	15.0	77.8	54.9	34	264	-15%	7%
200 m	**0.8 W/m/K**	14.1	26.7	20.2	104	>300	14%	-21%
	2 W/m/K	12.3	33.7	26.1	105	>300	-	-
	3.5 W/m/K	11.1	38.5	30.0	106	>300	-10%	14%

Table 4.3: Results for the study on the sensitivity of the production process to the thermal conductivity of the reservoir rock, after 300 years of production. Explanation as in Table 4.1. The simulation where λ_{cs} = 2 W/m/K is considered to be the Base Case.

For both cases with different reservoir thicknesses we observe that, the larger λ_{cs}, the smaller the well temperature decline. There is more thermal recharge, and it takes more time before thermal break-through occurs. With λ_{cs} = 0.8 W/m/K, the effect on the temperature decline in a reservoir of 50 meters thick is much larger than the effect on a reservoir of 200 meters thick. However, this is vice versa for the effect on the deviation in recharge ratio. When λ_{cs} = 3.5 W/m/K, the deviation of both temperature and recharge is less than with λ_{cs} = 0.8 W/m/K. But the way it affects the temperature and recharge is similar.

Interpretation

The confining layers provide the thermal energy that is used for the recharge. As discussed in 4.2.1 a larger thermal conductivity facilitates a larger heat flow. A larger thermal conductivity in the confining layers has the effect that more heat can be extracted from the confining layers. This heat flows to the reservoir and provides thermal recharge. A larger thermal conductivity in the confining layers results thus in more thermal recharge. More thermal recharge during production delays the temperature decline in the reservoir. When the reservoir is thinner, this effect is stronger.

4.3.2. Effect of Thermal Conductivity

The thermal conductivity of the matrix determines the amount of heat that can be conducted through the material. A larger thermal conductivity will result in a larger heat flow in the form of conduction.

In the model used for this study, both the heat flow in the reservoir and the heat flow from the confining layers to the reservoir, control the production profile. Therefore, a change in the thermal conductivity of the matrix of the reservoir, λ_{rs}, and the of confining layers, λ_{cs}, are likely to have effect. Furthermore, the impact that a change in the thermal conductivity has is determined by the reservoir thickness. First of all, this effect will be discussed for a reservoir of 50 meters thick, followed by a reservoir of 200 meters thick.

In a reservoir with a thickness of 50 meters, the effect of a change in thermal conductivity of the confining layers is greater than the effect of a change in thermal conductivity of the reservoir. These effects are summarized in Figure 4.4. The figure shows the effect of a change in thermal conductivity to the well temperature and the recharge ratio compared to the Base Case. The blue bars represent the results for a scenario where the thermal conductivity is smaller, and the orange bars represent the results for a scenario where the thermal conductivity is larger. The percentages indicate the deviation of the outcome compared to results of the the Base Case.

The figure shows that increase in thermal conductivity of the reservoir, has a minor impact on the production temperature. This can be explained by the fact that the recharge ratio remains almost constant compared to the Base Case. Part of the extra heat that causes the slight increase in production temperature, is conducted from the reservoir. Due to its higher thermal conductivity, heat can travel more easily through the reservoir, and therefore the heat flow has reached a larger area.

The decrease of thermal conductivity of the reservoir, has an even smaller impact on the recharge ratio. The effect on the production temperature decline is consistent with this. Less recharge will result in less energy in the reservoir that can be produced.

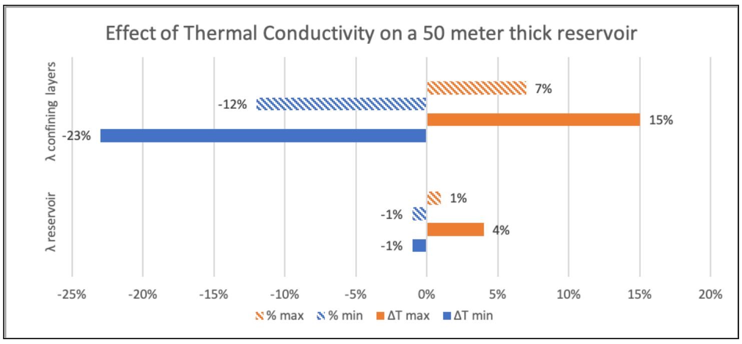


Figure 4.4: The effect of a change in thermal conductivity to the well temperature decline and recharge, for a reservoir of 50 meters thick, compared to the Base Case. The blue bars represent a change to a lower value and the orange bars represent a change to a higher value. The shaded bars represent the change in recharge ratio, and the solid bars represent the change in production temperature.

The effect that a change in the ability of the over- and underburden to conduct heat has, is significantly larger than the effect that a change in the thermal conductivity of the reservoir has. This can be explained by the fact that the confining layers control the recharge, and the recharge has a large influence on the production profile. With a decrease of thermal conductivity in the confining layers of approx. 50% (from $\lambda_{cs} = 2$ W/m/K to $\lambda_{cs} = 0.8$ W/m/K), the conductive heat flow from the over- and underburden towards the reservoir declines with approx. 8 PJ over 300 years (12% decline compared tot total recharge). This highlights the impact the confining layers have on the production of geothermal energy, especially for a thin reservoir.

Now we discuss the effects of the thermal conductivity on a reservoir of 200 meters thick. In a reservoir with a thickness of 200 meters, the impact of the change in thermal conductivity of the reservoir is significantly larger than for a thinner reservoir. On the other hand, the impact of a change in thermal conductivity of the confining layers on the well temperature, is smaller (Figure 4.5)

It is inherent that with a larger reservoir volume, i.e. increase in thickness, the energy content increases with the same rate. With a larger energy content in the reservoir itself, the production process is less dependent on the recharge. Relatively speaking, in a thicker reservoir more produced energy is coming from the reservoir itself, and the role that the confining layers play in the production process is smaller. As a result impact of recharge is smaller.

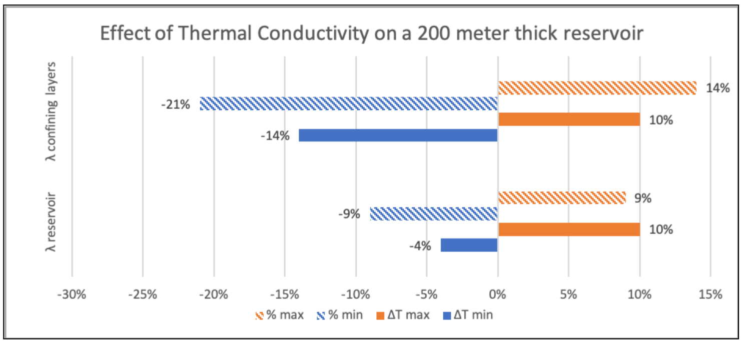


Figure 4.5: The effect of a change in thermal conductivity to the well temperature decline and recharge, for a reservoir of 200 meters thick, compared to the Base Case. Explanation as in Figure 4.4.

Considering the results presented in Section 4.2.1 and 4.3.1, the following conclusions can be drawn: The effect that the thermal conductivity has on the production profile is strongly dependent on the reservoir thickness. For a thinner reservoir, the thermal conductivity of the confining layers has more impact than the thermal conductivity of the reservoir. For a thicker reservoir, the thermal conductivity of the reservoir plays a more important role in the determination of the production profile than with a thinner reservoir. But also for a thicker reservoir, the thermal conductivity of the confining layers does have more impact than the thermal conductivity of the reservoir itself.

It should be noted, that with a change in thermal conductivity, a change in thermal gradient occurs (Equation 3.9). When changing the thermal conductivity to conduct these experiments, the temperature gradients have to change simultaneously. As a consequence, these experiments have, apart from a difference in thermal conductivity, a different thermal gradient distribution throughout the model.

This means that there is a difference in the initial temperature distribution between the models. This will have an influence on the results. However, to minimize this effect, we chose the average initial reservoir temperature to be constant for all models. The Section 6.2 in the Discussion Chapter, provides more information about the importance of modelling with the correct temperature gradient for the corresponding thermal conductivity.

Inequality over- and underburden

In addition to the cases that examine the effect of a change in the thermal conductivity, we also conducted an experiment to examine the effect of a different thermal conductivity in the over- and underburden. Appendix C.2.1 provides the results of these cases. The goal of these experiments was to investigate if one of the confining layers, either the over- or underburden has more impact on the production profile or that their impact is equal. Analyzing the results, we conclude that the impact of a change in thermal conductivity in either the over- or underburden is similar. Therefore, we decided not to focus on the individual effect of either the over- or underburden.

4.4. Case 4: Permeability of the confining layers

Case 4 discusses the fourth geological uncertainty, the permeability of the confining layers. This section presents the results and analyzes the effect of a change in the permeability of the confining layers.

4.4.1. Results

These tests examine the sensitivity of the production process to a change in the permeability of the confining layers. The Base Case, that is used as a reference, has a permeability of 0.01mD in the confining layers. This section presents the results of two other scenarios where the horizontal permeability in the confining layers is 10 mD and 100 mD. The permeability in the reservoir is kept constant at 200 mD, and the vertical- horizontal permeability ratio (k_v/k_h) remained at 0.1, for the entire model.

For a reservoir with the thickness of 50 meters, 100 meters, and 200 meters the effect of this parameter is reviewed. Table 4.4 summarizes the results of the scenarios. Appendix C.3.2 provides the corresponding graphs.

		Delta T	Recharge		TBT	TDP	Deviation	
	Permeability		%	PJ			**Temperature**	**Recharge**
50 m	**0.01 mD**	17.7	73.0	49.0	32	184	-	-
	10 mD	14.3	76.0	54.4	41	287	-19%	4%
	100 mD	6.4	83.8	67.2	119	>300	-64%	15%
100 m	**0.01 mD**	16.1	54.9	39.2	45	263	-	-
	10 mD	14.2	57.5	42.7	64	294	-12%	5%
	100 mD	6.8	68.5	55.8	124	>300	-58%	25%
200 m	**0.01 mD**	12.3	33.7	26.1	105	>300	-	-
	10 mD	11.2	35.5	27.5	111	>300	-9%	5%
	100 mD	5.8	45.9	37.5	152	>300	-53%	36%

Table 4.4: Results for the study on the sensitivity of the production process to the permeability of the confining layers, after 300 years of production. Explanation as in Table 4.1. The simulation where the permeability is 0.01 mD, is considered to be the Base Case.

The increase of the permeability in the confining layers has a positive effect on both the recharge and the production temperature. As a result, the thermal break-through time and the time it takes before the temperature decrease percentage of 25% is reached increases.
It is remarkable to see, that the overall effect is larger for a reservoir with a smaller thickness.

In addition we executed a test where the permeability in the confining layers is 0.0001 mD for a reservoir of 50 meters thick. The results, presented in Appendix C.3.1, show that a decrease in permeability in the confining layer compared to the Base Case, have no impact on the outcome. Due to the significant increase in computational time of this simulation, it was decided not to conduct the tests with a smaller permeability in the confining layers for the models with a reservoir thickness of 100 or 200 meters.

Interpretation

Section 4.3.1 discusses that the confining layers provide the energy that facilitates the thermal recharge. With a higher permeability in the confining layers, the convection of heat increases. This results in a larger heat flow from the confining layers to the reservoir. For a thinner reservoir, impact of the confining layers is larger. As a result, more thermal recharge occurs compared to a thicker reservoir. This has a positive effect on the well temperature progression.

4.4.2. Effect of Permeability

For an oil and gas reservoir it is essential to have an impermeable base and especially cap rock, to make sure that the oil or gas is sealed in.

However, for a geothermal reservoir this is less important because the pore fluid from the confining layers can also be produced. This section investigates what the effect is on geothermal production when the over- and underburden become less impermeable. Section 4.3.2 emphasizes the importance of heat exchange with the confining layers in form of conduction. With an increase in permeability, pore fluid is able to move more easily through the material. This contributes to the convective heat flow.

From the results of the experiment presented in Appendix C.3.1, we have learned that decreasing the permeability compared to the Base Case has a minimal effect on the production profile. Because, permeability determines to a large extend the convective heat flow through a rock, it appears the the convective heat flow forms a negligibly small part of the thermal recharge in the Base Case. The results presented in Table 4.4, show that when the permeability increases a thousand times, from 0.01 mD to 10 mD, the recharge ratio increases with approx. 5% for all reservoir thicknesses. This indicates that the heat flow by convection from the confining layers towards the reservoir is still relatively small, despite the large increase in permeability. When the permeability of the over- and underburden is 100 mD, the convective heat flow does form a significant part of the thermal recharge. This has a positive effect on the well temperature.

Figure 4.6 displays the well temperature after 300 years of production for increasing permeability in the over- and underburden. The results show that an increase in permeability in the confining layers has a positive effect on the well temperature. What is striking to see, is that the larger the permeability in the over- and underburden is, the smaller is the difference between the reservoirs with different thicknesses. This is due to the fact that with an increasing permeability more energy can flow from the over- and underburden towards the reservoir. With a permeability of 100 mD, the confining layers are half as permeable as the reservoir itself. Therefore, strictly speaking, the choice for a permeability of the over- and underburden of 100 mD may not be appropriate, as the over- and underburden are normally impermeable.

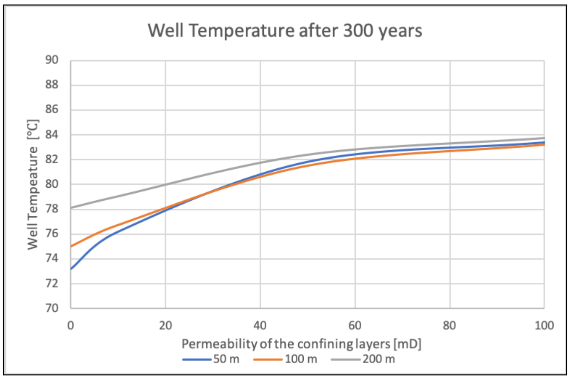


Figure 4.6: The well temperature after 300 years of production against the permeability of the confining layers. Plotted for a reservoir with a thickness of 50, 100 and 200 meters.

Looking at these results the following conclusion can be drawn: A larger permeability in the confining layers has a positive effect on the production process and enhances the sustainable use of a geothermal system. When the permeability is very large, this area might not be seen as over- or underburden but merely as a lesser permeable part of the reservoir.

Inequality over- and underburden

In addition to the case that examines the effect of a change in permeability in the confining layers, we also conducted an experiment to examine the effect of a different permeability in the over- and underburden. Appendix C.3.2 provides the results of these cases. The goal of these experiments was to investigate if one of the confining layers, either the over- or underburden has more impact on the production profile or that their impact is equal. Analyzing the results, we conclude that the impact of a large permeability in the over- or underburden is almost similar. Therefore, we decided not to focus on the individual effect of either the over- or underburden.

4.5. Effect of the Confining Layers

Section 4.3.2 and 4.4.2 discuss that a change in a geological parameter in the confining layers can have a substantial impact on the geothermal energy production. This section focuses on the overall impact that the over- and underburden have on the geothermal production process.

To be able to do this, the production process was simulated in a model without any confining layers. For this simulation only the reservoir rock was modeled. The upper and lower boundary, formed a no

fluid- and heat flow boundary. This simulation was executed for a model with reservoir thicknesses of 50, 100 and 200 meters.
Figure 4.7 displays the results of what the effect is on the production temperature when the confining layers are not included in the simulation.
It shows the well temperature drop after 300 years of production, with or without the confining layers modeled. The blue bars represent the well temperature drop when the confining layers are included in the simulation. The orange bars represent the well temperature drop when the confining layers are not included in the simulation. The percentages indicate the deviation in well temperature drop between the case with confining layers and without confining layers. This graph proves undisputedly that the confining layers play an important role in the geothermal production process. The results from the previous sections show that the thinner the reservoir, the larger the impact of the confining layers is, and the results shown in Figure 4.7 substantiate this theory.

In a reservoir with a thickness of 50 meters, the well temperature decline almost doubles when the confining layers are not included in the simulation. With an increase in thickness this impact slightly decreases, but for a reservoir of 200 meters thick, the well temperature drop still increases by two thirds when the confining layers are not taken into account.

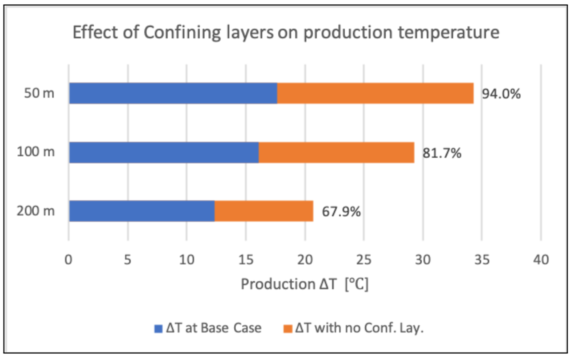


Figure 4.7: The well temperature decline after a production period of 300 years, for a reservoir of 50, 100 and 200 meters thick. The blue bars represent the Base Case, the orange bars represent the temperature decline for a model without confining layers. The percentage on the right-hand side is the deviation between these two cases.

Figure 4.8 gives an overview of the temperature distribution after 300 years of production for a reservoir of 50 meters thick. This figure indicates what the effect is on the temperature distribution when the over- and underburden are not included in the model. It shows the temperature distribution for the Base Case (left side) and a scenario where the over- and underburden are not included in the simulation of the production process (right side). The top right image shows a side view of the reservoir. This gives an idea of the size the area in the over- and underburden that is affected by the geothermal production, i.e. from where heat is extracted and has flowed towards the reservoir. Because of the extraction of heat from the confining layers, the cold front within the reservoir itself is less extensive compared to the case without the confining layers. When the confining layers aren't modeled, all the extracted heat comes from the reservoir itself. This results in a much larger temperature drop within the reservoir and a more extensive spread of the cold front. This figure shows the importance of the confining layers in the production process.

From this section together with Sections 4.1.2, 4.3.2 and 4.4.2 can be concluded that the confining layers have a large impact on the production profile of geothermal energy. They supply a lot of the heat that is extracted during the geothermal production and are therefore a part of the geothermal system that should not be overlooked.

4.6. The effects of geological uncertainties

When making a field development plan for a geothermal reservoir, there are always uncertainties regarding the geological parameters. With the possibility that there is an error in the assumed value of a parameter, the production profile could turn out to be a lot different from the pre-drill prediction. Therefore, it is important to know what geological parameters have a large effect and what parameters have a minor impact on the production profile.
Moreover, with a clear understanding of what the impact of a parameter on the production profile is, the thermal activities that play an important role in determining the production profile can be defined.

The geological parameter that has the largest effect is the reservoir thickness. The well temperature deceases the fastest for a thinner reservoir, which stimulates a larger flow of thermal recharge. As a result, more energy per representative volume can be produced for the same temperature drop. Additionally, the thickness of the reservoir determines to a considerable degree what the impact is of other geological uncertainties. Geological uncertainties concerning the reservoir have more effect when the reservoir thickness is larger. When there is a thinner reservoir, the geological uncertainties concerning the confining layers have a larger impact on the production process.

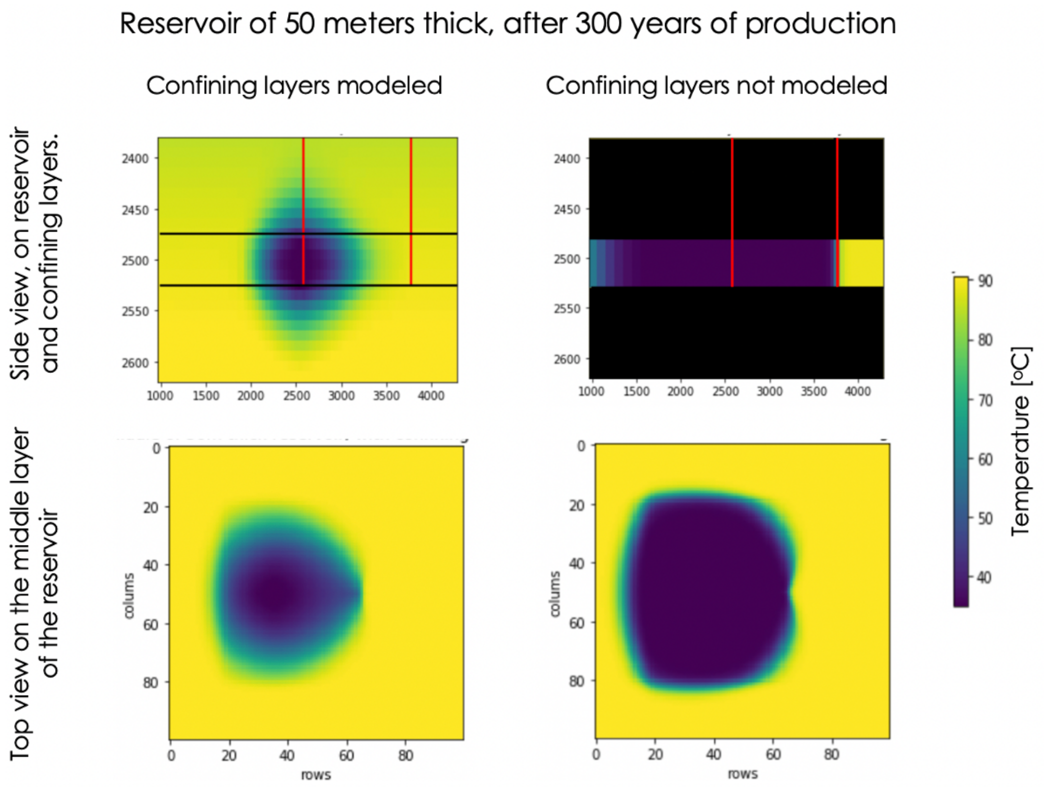


Figure 4.8: Temperature distribution in the model, after 300 years of production. On the left-hand side the images show the outcome of the model where the over- and underburden are included in the simulation. On the right-hand side, the images show the outcome of the model where no confining layers were taken into account. The top two images show a side view of the reservoir with part of the over- and underburden on the axis which crosses the wells. The bottom two images show a top view of the middle layer of the reservoir. The red lines represent the wells, the black lines demonstrate the top and lower boundary of the reservoir.

B. Production Parameters

The production strategy has impact on the production profile of a geothermal reservoir. Unlike the geological uncertainties (discussed in Section 4.6) the production parameters can be controlled. This part of Chapter 4 presents what the effects are of production parameters on the production process. These results are analyzed to optimise the production process in order to be able to produce a sufficient amount of energy in a sustainable way.
The following two production parameters are analyzed.

- Case 5: The production rate (4.7)
- Case 6: The well spacing (4.8)

Every section consists of two subsections. The first subsection presents the results of the sensitivity study of the production parameters to the production process. The second subsection contains an analysis of the effect of the parameter.

4.7. Case 5: Production Rate

Case 5 evaluates the first production parameter, the production rate. This section presents the results and analyzes the effect of a change in the production rate.

4.7.1. Results

This case investigates the effects of the production rate (Q [m^3/hr]). For this case, two types of tests are executed. The first tests examine the effect of a production rate proportional the to reservoir thickness. A reservoir with a thickness of 50, 100 and 200 meters has a production rate of respectively 150, 300 and 600 m^3/hr. The top three rows of Table 4.5 present the results of these tests. In Appendix C.4 Figure C.13 and C.14 provide the corresponding graphs.

The second part of tests concern a reservoir with a thickness of 200 meters, with a production rate of 150, 250, 400 and 600 m^3/hr. The bottom four rows of Table 4.5 present the outcomes of these simulations.

		Delta T	**Recharge**		**TBT**	**TDP**	**Deviation**	
	Q [m^3/hr]		**%**	**PJ**			**Temperature**	**Recharge**
50 m	**150**	17.7	73.0	49.0	32	184	-	-
100 m	**300**	24.4	55.5	66.6	30	86	38%	-24%
200 m	**600**	28.7	35.3	75.6	26	63	62%	-52%
200 m	**150**	12.3	33.7	26.1	105	>300	-	-
	250	19.6	34.5	39.7	62	179	59%	2%
	400	24.9	35.0	56.5	39	101	102%	4%
	600	28.7	35.3	75.6	26	63	132%	5%

Table 4.5: Results for the study on the sensitivity of the production process to the production rate. Explanation as in Table 4.1. For the top three rows, the deviation of the results are compared to the case with reservoir thickness 50 meters and Q = 150 m^3/hr. In the bottom three rows, the deviation of the results are compared to the case with a reservoir thickness of 50 meters and Q = 150 m^3/hr.

For the first three cases, where the production rate increases proportionally with the reservoir thickness, the well temperature and the recharge ratio both decreases with an increase in reservoir thickness. However, the absolute amount of thermal recharge does increase.

For the experiments with a different production rate and a reservoir of 200 meters thick, the well temperature decreases with increase in production rate. However, the recharge ratio remains almost the same for all four cases. This result appears to have a relation to the increase in absolute recharge.

Interpretations

With a production rate relative to the reservoir thickness, one could expect that the production temperature remains stable. With an increase in reservoir volume, the amount of extracted heat increases with the same rate. But in practice, due to the relatively lower recharge over the same period of time, the well temperature decreases.

The increase in thermal recharge [PJ] with the increase in production rate for a reservoir with the same thickness, causes a lower decrease in well temperature than the increase in production rate. The recharge ratio even increases. When the production rate increases, more heat is extracted. This results in a larger temperature difference between the reservoir and the over and under burden, which facilitates more recharge.

4.7.2. Effect of the production rate

The rate at which geothermal energy is produced, will have a great impact on the lifetime of a geothermal project. And when the goal of a geothermal project is to be able to sustainably produce energy, choosing the correct production rate is vital.

Proportional production rate

When the production rate proportionally increases with the reservoir volume, i.e. the thickness, one might expect that the production profile remains equal. However, the results summarized in Table 4.5 suggest otherwise. The information that is presented indicate that with an increase in thickness, and thus production rate, the temperature in the reservoir decreases faster.

Figure 4.9 visualizes this. The figure shows the temperature distribution in the three cases after 300 years of production. It provides both a top view image of the middle of the reservoir and a side view image of the reservoir and part of the over- and underburden. The figure shows that the cold front is more extensive for a thicker reservoir with a larger production rate. As a result the well temperature in the reservoir of 200 meters thick with a production rate of 600 m^3/hr is lower after 300 years of production.

This effect is caused by the difference in recharge ratio. The recharge ratio decreases with an increase in thickness and production rate. This has two causes.

First of all, we will discuss the effect of the increase in thickness. The analyses in Section 4.6 indicate that the recharge ratio decreases with an increase in reservoir thickness, due to a smaller influence of the over- and under burden on the reservoir.

The second cause concerns the method of how the recharge ratio is calculated (Equation 3.1.5). The recharge ratio is the ratio between the amount of recharged thermal energy and the amount of produced thermal energy. An increase of the production rate results in an increase in the amount of

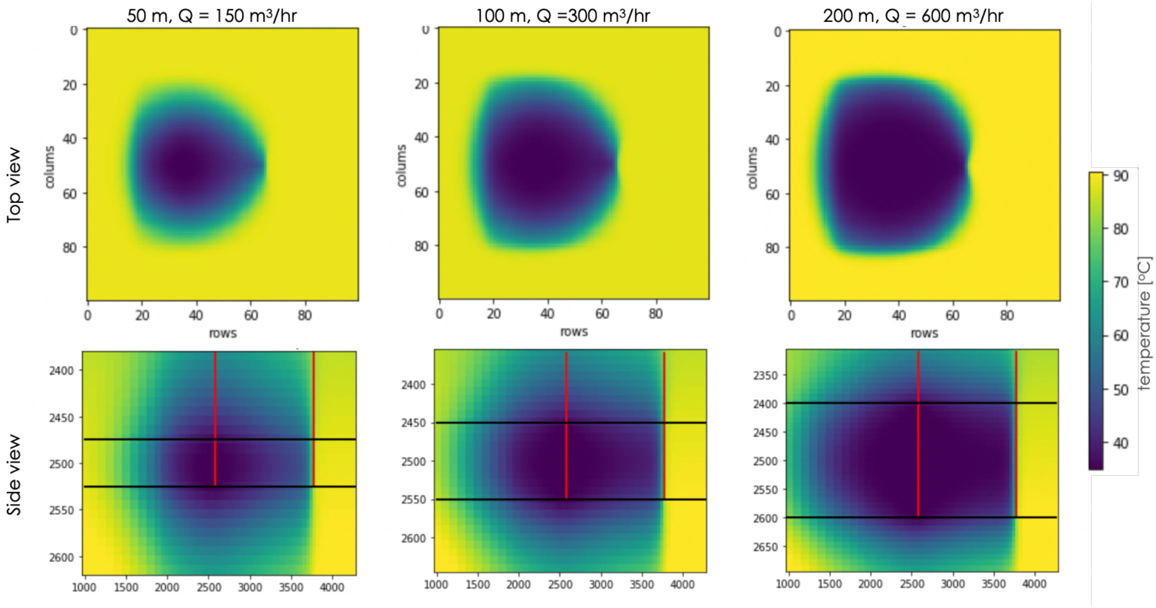


Figure 4.9: Temperature distribution after 300 years of production for cases with the production rate relative to the reservoir thickness. The top three images show a top view of the middle layer of the reservoir. The bottom three images show a side view of the reservoir (in between the black lines). It is important to mention that the *z*-axis is not similar for the three cases. The red lines represent the interjection and production wells.

produced thermal energy. With the produced energy as the denominator of the recharge ratio fraction, this will result in the decrease of the recharge ratio, which causes a faster decline in production temperature.

This effect is slightly attenuated by the fact that the absolute amount of recharge does increase with increasing reservoir thickness and production rate. The results presented in Table 4.5, show a 50% increase of absolute thermal recharge between a reservoir of 50m and 200m. One could expect that, because the production rate is proportionally equal, the distribution of cold water in the reservoir would be equal. And that with the same the thermal recharge would be equal for the three different cases. This is however not the case. Figure 4.10 shows the temperature distribution in the layer directly on top of the reservoir after 300 years of production. It shows that the size of the area that has cooled down, increases with an increase in reservoir thickness and production rate. This results in more thermal recharge from the over- and underburden towards the reservoir. The fact that the cold front is more extensive for a thicker reservoir, is due to the fact that the recharge ratio is lower. For a thicker reservoir a smaller part of the produced heat has flowed back into the reservoir compared to a thinner reservoir. Therefore, relatively more thermal energy has been extracted from the reservoir itself, causing a larger cold temperature front.

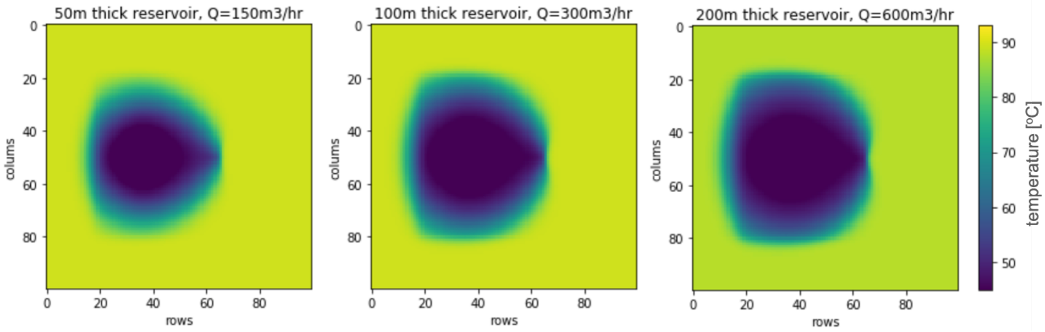
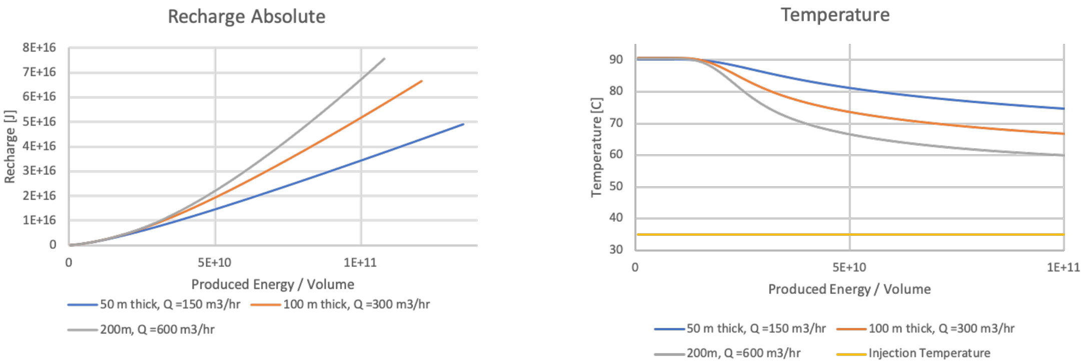


Figure 4.10: Temperature distribution in the boundary layer between the reservoir and the overburden after 300 years of production.

Based on these findings, it is argued that in order to keep the decrease in productivity minimal and thus to produce sustainably, the production rate should be proportionally smaller for a thicker reservoir.



(a) The absolute amount of thermal energy recharged from the over- and under burden to the reservoir.

(b) The well temperature.

Figure 4.11: Energy produced divided by a representative volume. For production rate increases proportional to the reservoir thickness.

This statement is substantiated by analyzing the results showed in Figure 4.11. It shows the well temperature and the amount of thermal recharge against the produced energy divided by a representative volume for the reservoir (Equation 3.25). This is done to be able to compare the results on a scale with minimal effect of a difference in reservoir volume.

The results shown in Figure 4.11 demonstrate that proportionally, when the same amount of energy is produced per proportional volume, e.g. $1 * 10^{11}$ [J/m^3], the recharged thermal energy is larger for a thicker reservoir with a high production rate. However, the well temperature is higher for a thinner reservoir. This is explained by considering the physics behind recharge. Thermal recharge is driven by temperature difference. With a lower temperature in the reservoir, more energy will be recharged. When more recharge occurs, more energy from the over- and underburden is produced. Therefore, it is argued that producing with a high production rate is more effective. However, from a sustainability point of view, the thinner reservoir has a higher well temperature for the same amount of produced energy per volume. As a result more energy can be produced without having the production temperature drop below the accepted range.

Using these results it can be concluded that, with a production rate proportional to the reservoir thickness, the temperature in the reservoir has dropped more for a thicker reservoir. As a result more thermal energy flows from the over- and underburden towards the reservoir per produced volume. With this larger thermal recharge more energy is extracted from the confining layers. Therefore, the extraction of heat from the over- and under burden is more efficient. However, a larger temperature drop has a negative influence on the sustainability of the geothermal project. In order to produce sustainably, a thinner reservoir is more favourable because more energy can be extracted per representative reservoir volume for the same well temperature drop.

Increase in production rate

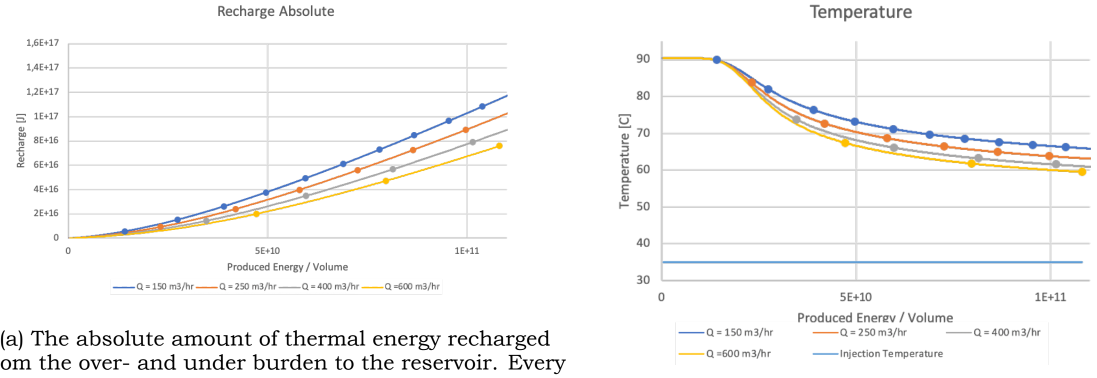
Table 4.5 and Appendix C.4, Figure C.13, display the results of the effect of an increase in production rate for a reservoir with the same thickness. What is striking to see, is that the recharge ratio is unaffected by a change in production rate. The increase in the extraction of energy, i.e. increase in production rate, is compensated by an increase in the absolute amount of thermal energy that flows from the over- and under burden towards the reservoir.

Figure 4.12a gives another view on these results. It displays the total amount of recharged energy against the produced volume divided by a representative volume of the reservoir (Equation 3.25). The graph shows that, when a certain amount of energy per volume is produced e.g. $1 * 10^{11}$ [J/m^3], producing at a lower rate generates more recharge.

Figure 4.12b shows the production temperature against the amount of produced energy per volume. The temperature decline is slightly larger for a higher production rate. This is the result of the smaller amount of recharge.

It should be noted that the time it takes to produce the same amount of energy per volume, is roughly reversely proportional to the production rate. When comparing the case with a production rate of 150 m^3/hr to 600 m^3/hr at the point when $1 * 10^{11}$ [J/m^3] is produced, the following three aspects should be considered.

Firstly, with an increase of 300% in production rate, the thermal energy that is recharged decreases by 34%, from 103 PJ to 67 PJ. Secondly, this decline in recharge has consequences for the production temperature. When the same amount of energy is produced, the temperature decline is 22.6% larger



(a) The absolute amount of thermal energy recharged from the over- and under burden to the reservoir. Every 100 years of production is represented by a circle on the line.

(b) The well temperature during production. Every 100 years of production is represented by a circle on the line.

Figure 4.12: The effect of production rate on a reservoir of 200 meters thick, on the total amount of energy produced per representative volume.

with a higher production rate. The well temperature drop increases from 25,19 ^{o}C to 30.9 ^{o}C. Thirdly, the time it takes to produce the same amount of energy per volume almost quadruples.

These three findings play an important role in determining the production strategy. The first two findings indicate that producing at a lower rate is more sustainable. The results presented in Section 4.7, indicate that the lifetime of a reservoir increases with a decrease in production rate. This makes sense, when less energy is extracted in a unit of time, the longer it will take before the same amount of energy is extracted. The results presented in Figure 4.12 show that it is also more sustainable to produce at a low rate with respect to the amount of produced energy. When producing the same amount of energy per representative volume, the recharge is higher and the temperature decline is lower for a geothermal project that maintains a lower production rate. The rate at which the reservoir cools down decreases. From these results we draw the conclusion that it is more sustainable to produce at a lower rate.

Nonetheless, the third finding, that gives an indication about the time, is significant. One could argue that a geothermal system is designed to serve a purpose and with a quadrupling of the production time, the purpose is lost. A geothermal system should produce a sufficient amount of energy to supply the demand. When decreasing the production rate in order to obtain more recharge, and decrease the well temperature drop, the demand for energy may not be fed.

Therefore, it may not always be possible to produce at a low rate in order to be sustainable, dependent on the demand for energy.

Another aspect from Figure 4.12b that is important to mention, is that the well temperature appears to approach an asymptote at the end of the simulation. The results indicate that with a higher production rate the temperature of the asymptote is lower. This asymptotic behaviour of the well temperature is further discussed in Section 6.3 of the Discussion Chapter.

4.8. Case 6: Well Spacing

Case 6 evaluates the second production parameter, the well spacing, i.e. the distance between injector and producing well. This section presents the results and analyzes the effect of a change in well spacing.

4.8.1. Results

These tests examine the sensitivity of the production process to a change in the well spacing. The Base Case has a well spacing of 1200 meters. The two other tests have a well spacing of 1000 meters and 1500 meters. For a reservoir with a thickness of 50 and 200 meters we reviewed the effect of this parameter.

Table 4.6 gives a summary of the results, and Appendix C.5 provides the corresponding graphs.

With an increase in well spacing, the decline in well temperature decreases, independent of the reservoir thickness. The recharge ratio is hardly affected by a change in well spacing. The absolute recharge increases slightly with an increase in the well spacing. A change in well spacing has the largest effect on the thermal break-through time and the time it takes the well has decreased a tem-

	Well Spacing [m]	Delta T	Recharge		TBT	TDP	Deviation	
			%	PJ			Temperature	Recharge
50 m	**1000**	22.1	73.2	44.6	20	100	25%	0%
	1200	17.7	73.0	49.0	32	184	-	-
	1500	11.7	72.7	54.3	57	>300	-34%	-0.5%
200 m	**1000**	17.7	34.3	24.5	68	214	44%	1.7%
	1200	12.3	33.7	26.1	105	>300	-	-
	1500	5.1	33.1	27.3	176	>300	-59%	-2%

Table 4.6: Results for the study on the sensitivity of the production process to well spacing, after 300 years of production. Explanation as in Table 4.1. The simulation where the well spacing is 1200 meters, is considered to be the Base Case.

perature decrease percentage of 25%. The deviation in well temperature and recharge ratio is larger for a model with a thicker reservoir.

Interpretation

It is expected that, with an increase in well spacing, the total drop of the well temperature decreases. This is due to the fact that with an increase in well spacing, the reservoir volume from which energy is extracted, increases. An increase in reservoir thickness enhances this effect.

4.8.2. Effect of well spacing

When designing a production plan, one of the parameters that should be chosen very carefully is the well spacing. Table 4.6 and in the graphs in Appendix C.5 display the effects of a difference in well spacing on the recharge ratio and the well temperature, measured over time.

It is not surprising that an increase in well spacing has a positive effect on the recharge ratio and the well temperature. Due to a larger distance between the two wells, the area from where heat is extracted, increases. Both in the reservoir and in the confining layers.

Figure 4.13 represents a side view of the reservoir and shows the temperature distribution after 300 years of production. With a larger well spacing, the area from where heat is extracted, i.e. that has cooled down, increases.

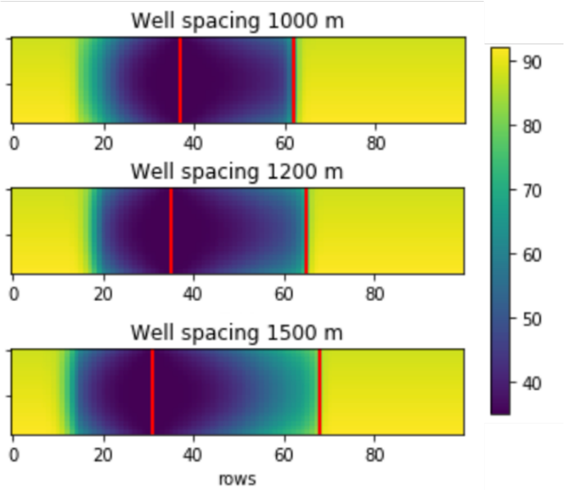


Figure 4.13: Temperature distribution in the reservoir with various well spacing. Side view of a 200 meters thick reservoir, after 300 years of production. The left and right red lines represent respectively the injection and production wells.

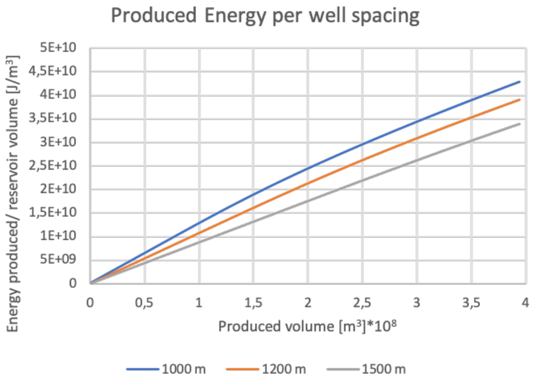


Figure 4.14: The effect of the well spacing on the produced energy for a reservoir of 200 meters thick, during 300 years of production. On the x-axis the produced volume with a production rate of 150 m^3/hr , on the y-axis the produced energy per volume between injection and producing well.

However, the fact that a larger area is affected does not mean that the heat extraction is more efficient. Figure 4.14 shows the produced energy per representative reservoir volume (Equation 3.25), against the total produced volume. The graph demonstrates that, with a smaller distance between the injection and producing well, the energy that is produced from the representative volume is larger. In other words, when the wells are placed closer to each other, the area that is affected by the production is smaller, however the heat extraction in this area is more extensive.

A more extensive production of the energy per reservoir volume and thus a higher energy output, increases the temperature drop in the affected area of the reservoir. This will have a negative effect on the sustainability of the reservoir.

In addition to the effect on the amount of produced energy per representative volume, the well spacing does also have effect on the movement of the thermal front. Figure 4.15 shows the temperature distribution in the reservoir between the injection and producing well, after 60 years of production. The figure shows that the cold front moves faster when the injection and producing well are placed closer to each other.

This can be explained by analyzing the effect of the producing well. By extracting pore fluid from the rocks, the pressure in the rocks surrounding the producer will drop. The exact opposite happens near the injection well, water is pumped into the subsurface that causes a pressure increase in the surrounding rocks. As a result, a pressure difference in the reservoir will occur.

In the beginning of the production, this pressure difference does not have an effect, due to the large distance between the wells. The injected colder water spreads evenly in all directions. After a certain amount of time, the cold front will start to feel the effect of the producing well. The movement of the cold front will shift more towards the producing well. The shorter the distance between the wells is, the earlier in production process this event will occur.

Figure 4.15 shows the temperature in the reservoir after 60 years of production, against the distance from the injection well towards the production well. It shows that for a well distance of 1000 meters, the cold front, i.e. decline in temperature, has traveled almost 1000 meters. When the well distance is 1500 meters the cold front has only moved 750 meters towards the producing well, during the same time.

These results can be summarized as follows: First of all, a larger well distance will result in a longer production time and more thermal recharge. Secondly, more energy per volume is extracted when the wells are placed closer to each other. This will result in a more efficient production of energy per unit volume, but also in a larger temperature drop in the reservoir. Thirdly, the well distance has influence on the mitigation velocity of the cold front towards the production well. With a larger well distance, the cold front moves slower. Therefore, the time it takes the cold front to reach the production well increases relatively.

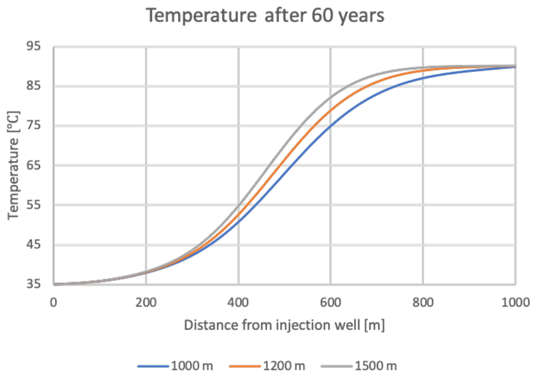


Figure 4.15: The temperature in the reservoir against distance from the injection well after 60 years of production. Plotted for a model with well spacing of 100, 1200 and 1500 meters.

From these findings can be concluded that it is more sustainable to increase the well distance, but that more energy per unit volume can be extracted when the wells are placed closer to each other.

4.9. Effect production parameters

When making a production design and strategy, the production parameters have a large impact on the sustainable development of a geothermal system. The production parameter that has the largest effect on the production profile is the production rate. With a production rate proportional to the reservoir thickness, more energy can be extracted per representative reservoir volume from a thinner reservoir, for the same well temperature drop. For a reservoir with a constant thickness and a changing production rate, the amount of energy that can be produced from a representative reservoir volume decreases with a higher production rate. Therefore, producing with a lower rate enhances the sustainable use of a geothermal system.

The effect that the well spacing has on the production profile, is smaller than the effect of the production rate. However, it still plays an important role in the sustainable production design and strategy. An increase in well spacing enhances the sustainable use of a geothermal system, as it reduces the rate of the well temperature drop.

5

Production Optimisation

Chapter 4 presents what the effect is that a number of parameters have on the production process. The parameters are divided into geological uncertainties and production parameters. However, in practice all parameters are inextricably connected. This means that, if one parameters appears to be different, the effect of all the other parameters will undeniably change as well. Therefore, it is difficult to assess the separate effect of a single parameter.

This Chapter provides a production optimisation for various geothermal systems taking all of the effects of geological uncertainties and production parameters into consideration. The goal is to find a production design and strategy that allows us to sustainably produce geothermal energy for every various geothermal system.

In line with the rest of this report, this production optimisation is divided into two parts. Section 5.1 discusses the geological uncertainties. Multiple production plans are made, that can account for the geological uncertainties. Section 5.2 discusses the production parameters, for multiple production designs the production plan is optimised to generate a sustainable output. In addition to this, section 5.3 discusses the renewability of a geothermal system and how that can contribute to the sustainability.

5.1. Geological uncertainties

When making a production plan for a geothermal project, the geological uncertainties should be taken into account. Because a change in a geological parameter can cause a shift in the production profile. When it appears that after drilling the doublet, the geology happens to be different, the production plan should be changed. But how can the production parameters be altered in order to reach the production goal? This section will provide a production plan for various scenarios where the geology appears to be different.

The results presented in Chapter 4 showed that the geological parameter that has the largest impact on the production profile is the reservoir thickness. The degree of effect of the other parameters, both geological and production, are dependent on the reservoir thickness.
Section 4.5 states that the effect of the confining layers increases with a decrease in reservoir thickness. Therefore, it is not surprising that the effect of the geological uncertainties concerning the over- and under burden, i.e. the thermal conductivity and the permeability, are larger for a thinner reservoir than for a thicker reservoir.
This effect is the result of the recharge of thermal energy from the confining layers to the reservoir. The thermal recharge has a large impact on the geothermal production profile, the more recharge the lower the well temperature decline. Thermal recharge is stimulated by a temperature difference between reservoir and over- and under burden. The larger the temperature difference, the larger the thermal recharge is. An increase in temperature difference can be created by altering the production parameters. A smaller production rate or a larger well distance both have a positive impact on the amount of thermal recharge.

The production optimisations made for this study are based on the Base Case with a reservoir thickness of 100 meters (Table 3.1). The goal is to produce for at least 100 years without having the well temperature drop below 85 ^{o}C. We have chosen these specifics to meet the definition of sustainable development of the World Commission on Environment and Development (1988).

Figure 5.1 shows the well temperature during 100 years of production for the Base Case. During production the temperature declines from 90.25 ^{o}C to 85.1 ^{o}C, with a constant production rate of 150 m^3/hr. This means that the production goal will be reached, if the subsurface is exactly similar to

the Base Case. However, when it appears that a certain parameter is different from what is expected beforehand, the production plan should be altered. When the wells have already been drilled, the easiest way to do this, is by changing the production rate.
For this production optimisation we have simulated four possible scenarios. Table 5.1 shows these four scenarios that could occur, and how they differ from the Base Case. For every scenario we have suggested a production rate in order to reach the production goals.

All of these four scenarios are designed to meet the production goal. When a heat transfer system has already been built, these scenarios can be examined. To ensure that the production temperature will be within the systems range. Now these scenarios will be further elaborated on

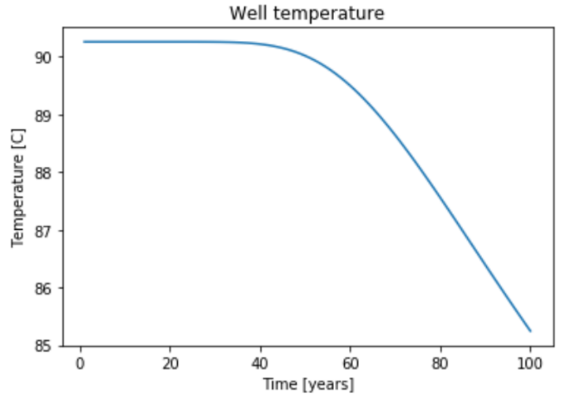


Figure 5.1: The well temperature during 100 years of production.

For the first scenario the thickness of the reservoir proves to be different. Scenario 1 is split into part A and B. Scenario 1A has a smaller reservoir thickness and scenario 1B has a larger reservoir thickness. It can be concluded, that when the situation in the subsurface is better than was expected, the production rate can be increased. When there is less potential in the subsurface the production rate should be decreased. For scenario 1A and 1B this means that the production rate should be respectively decreased and increased.

Scenario 2 holds that the thermal conductivity of the reservoir appears to be different from what was expected. Scenario 2 splits into part A and B. In scenario 2A the thermal conductivity is smaller, in scenario 2B the thermal conductivity is larger. It can be concluded that with a smaller thermal conductivity in the reservoir, heat travels at a slower rate through the reservoir, therefore the production rate should be decreased to ensure that the temperature decline remains within bounds. For a larger thermal conductivity it is the other way around, and therefore the production rate can be increased to maximize the energy extraction from the reservoir.

Scenario 3 examines the thermal conductivity of the over- and under burden, because when the thermal conductivity of the over- and under burden appears to be different from what was expected, the production plan will have to be altered as well. Scenario 3A and 3B represent a model with a respectively smaller and larger thermal conductivity of the confining layers. The production rate should be corrected when thermal conductivity in the over- and under burden appears to be different, because the confining layers control the thermal recharge, and a larger thermal conductivity results in more recharge. As a consequence the rate at which the well temperature drops decreases. Therefore, it can be concluded that for scenario 3A a lower production rate should be maintained and a higher production rate for scenario 3B.

Scenario 4 shows that the permeability of the confining layers appears to be larger than what was expected. A larger permeability in the over- and under burden will increase the thermal recharge to the reservoir. In order to extract the energy that is available in the reservoir, the production rate should be increased.

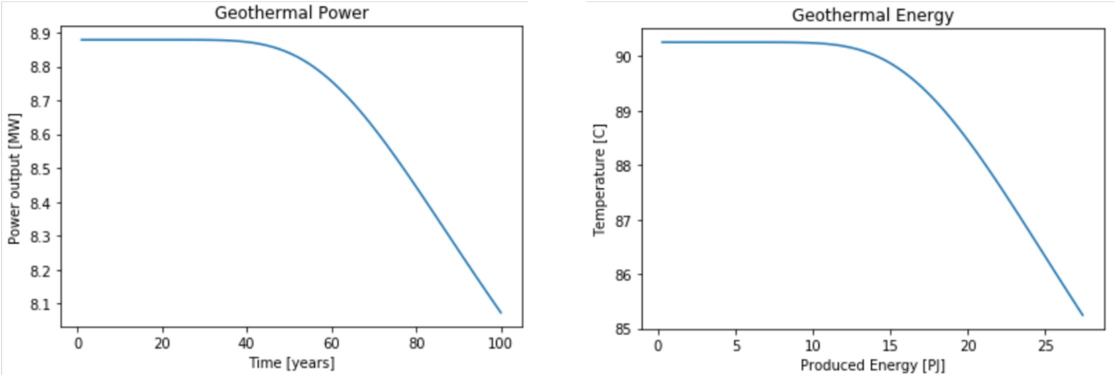
Scenario	**Deviation**	**Production Rate**
1A	Reservoir Thickness = 50 m	Q = 100 m^3/hr
1B	Reservoir thickness = 200 m	Q = 250 m^3/hr
2A	λ_{res} = 1.5 W/m/K	Q = 143 m^3/hr
2B	λ_{res} = 5 W/m/K	Q = 160 m^3/hr
3A	$\lambda_{conf\ lay}$ = 0.8 W/m/K	Q = 137 m^3/hr
3B	$\lambda_{conf\ lay}$ = 3.5 W/m/K	Q = 162 m^3/hr
4	$k_{conf\ lay}$ = 10 mD	Q = 173 m^3/hr

Table 5.1: Geological deviation and the change in production rate

Reviewing all of these results it can be concluded that a change in the reservoir thickness has the largest effect on the production plan. Contemplating the results presented in Table 5.1, we can formulate the following rule of thumb; When the reservoir thickness doubles, the production rate can be increased by 50% to maintain the same rate of well temperature decline.

5.2. Production parameters

Before any system at the surface can be built, choices should be made regarding the production output of a geothermal reservoir. The following cases discusses the potential of a geothermal reservoir, and what the outputs are for multiple production strategies. The starting point is the Base Case. Assuming that the geological parameters are correct, numerous production plans are designed to obtain different production outputs.



(a) The geothermal power output in megawatt over a period of 100 years.

(b) The well temperature decline against the time integrated produced geothermal energy.

Figure 5.2: The production output for the Base Case.

Firstly we will discuss the production output of the Base Case. Figure 5.2a and Figure 5.2b show the production output for the Base Case after 100 years of production. During those 100 years of production, the well temperature declines by 5.15 ^{o}C to 85.1 ^{o}C. Corresponding to that is the the power output, it started at almost 8.9 MW and retained that level for 40 years, before gradually declining to 8.1 MW. After 100 years, 27.7 PJ of energy has been produced from the geothermal reservoir.

To make a production strategy, it should be taken into account that both the production rate and the well spacing have a large effect on the output of a reservoir. Multiple production plans with variations in production rate and well spacing are tested, and the production output is monitored. Table 5.2 summarizes the results.

Well Spacing	Production rate	Temperature	Energy [PJ]	Power [MW]	Constant [years]
1000 m	100 m^3/hr	85.0 ^{o}C	18.6	6.0 - 5.4	40
	150 m^3/hr	79.3 ^{o}C	26.6	9.0 - 7.2	30
	200 m^3/hr	74.9 ^{o}C	33.5	11.9 - 8.7	20
1200 m	100 m^3/hr	89.2 ^{o}C	19.0	6.0 - 5.85	60
	150 m^3/hr	85.1 ^{o}C	27.7	9.0 - 8.1	40
	200 m^3/hr	81.2 ^{o}C	36.0	11.9 - 9.9	35
	250 m^3/hr	77.3 ^{o}C	43.3	14.9 - 11.5	30
	300 m^3/hr	75.2 ^{o}C	50.0	17.9 - 12.9	25
1500 m	200 m^3/hr	87.2 ^{o}C	37.3	11.9 - 11.2	55
	250 m^3/hr	84.2 ^{o}C	45.9	14.9 - 13.2	45
	300 m^3/hr	81.4 ^{o}C	53.8	17.9 - 14.9	40
	350 m^3/hr	79.1 ^{o}C	61.3	20.7 - 16.5	35

Table 5.2: Production output after 100 years of production. From left tot right the columns give the following information: The well distance; the production rate; the well temperature after of 100 years of production; the total amount of produced energy [PJ] during 100 years; the power output [MW] at the start of production and at the end of 100 years of production; the production time [years] during which the well temperature is constant, after that the temperature starts to decline.

The first and second column, in Table 5.2, provide information about the production design and strategy. The first column gives the distance between the injection and production well and second column shows the production rate. The third column displays the well temperature after 100 years of production. The initial temperature in every case is 90.25 ^{o}C. The third column therefore gives an indication of the well temperature decline. The fourth column shows the total amount of produced thermal energy in petajoule during 100 years of production. Column number five gives the power output at the beginning of the production and after 100 years. Due to the drop in well temperature, the power that can be produced from the well will decrease with it. The last column shows the length of time that a constant temperature could be produced before the decline in temperature and power output begins.

The correct production strategy can be chosen, i.e. the well distance and the production rate, depending on the energy demand or the shape of the reservoir.

Section 2.2 describes that according to the Master Plan for Geothermal Energy in the Netherlands (Schoof et al., 2018), in 2030 175 geothermal doublets should supply 46.5 PJ of energy (5% of the total energy demand). Generally speaking this means that every doublet should produce an average of 0.265 PJ of energy each year, which corresponds to an average power output of 8.4 MW.

For every well spacing a production strategy will be determined, because the geology is the main factor that determines what well spacing is allowed. First, with a well spacing of 1000 meters, a production rate of 100 m^3/hr should be maintained to make sure that the well temperature does not drop below 85.0 ^oC. However, this means that the energy output is less than what one doublet should produce. If the demand of 8.4 MW is to be met, the geothermal system should be redesigned so that it can cope with a production temperature of below 80.0 ^oC.
Secondly, if geology allows for a well distance of 1200 meters, and a production rate of 150 m^3/hr is maintained, the goals will be reached.
Thirdly, when the wells are placed 1500 meters apart, 250 m^3/hr of water can be produced if the geothermal system allows well a temperature of 84.2 ^oC. The first 45 years of the expected production output is 14.8 MW, after that time the decline starts. At the end of 100 years of production, the output has declined to 13.2 MW, and a total of 45.9 PJ has been produced.
From these production strategies the following rule of thumb can be formulated: When the well distance increases by 20%, the production rate can be increased by 50% to maintain the same rate of well temperature decline. In other words, it can be concluded that the larger the well spacing is that the geology allows for, the larger the energy output is.

5.3. Renewability

This thesis does not only study what happens to a geothermal system during production, but also examines what happens to it after production has stopped. With this we investigate the renewability of a geothermal system, and how that can contribute to a sustainable use of it.

Section 2.4 describes that renewability is the property of the resource that determines if it returns to its original state in a natural way after extraction has stopped. Preferably within the same time scale it took to extract the resource.

The following experiment tests the renewability of a geothermal reservoir. After the production stops, the temperature in the reservoir, is monitored. This is done to examine whether or not the reservoir will return to its original state, and how long that will take.

We simulated 100 years of production from the Base Case model with a reservoir thickness of 50 meters (Table 3.1). After this production period, another 1300 years is simulated without any production. During the complete simulation time, the well temperature and the recharge ratio are monitored. Figure 5.3 shows the well temperature and recharge ratio development during this simulation, and Table 5.3 gives a summarized overview of these results.

The graph on the left shows that during the production period of 100 years, the well temperature drops from 90.3 ^oC to 81.5 ^oC. During the time of production, 60% of the produced thermal energy has already flowed back into the reservoir.

In the beginning, right after the production has stopped, the reservoir immediately starts to reheat. The temperature of the reservoir surrounding the production well, has increased by more than 4^oC to a temperature of 85.8 ^oC, in the 100 years after geothermal production has stopped. This temperature increase is caused by the thermal recharge. At this point, 76.9% of all the energy that is produced has already flowed back from the over- and under burden towards the reservoir.

At the end of the simulation, the temperature of the reservoir surrounding the production well is 88.8 ^oC. This temperature is 1.5 ^oC lower than the original state, before production started. This is the result of a recharge of 92.6% of the produced energy.

Immediately after the production has stopped, the temperature in the reservoir increases. Rapidly at first, but about 200 years after production stops, the rate at which the temperature rises decreases. This rapid increase in temperature is caused by the recharge of energy from the confining layers towards the reservoir. Thermal recharge is driven by a difference in temperature, and is most effective with a large temperature difference. As the reservoir heats up, the difference in temperature between

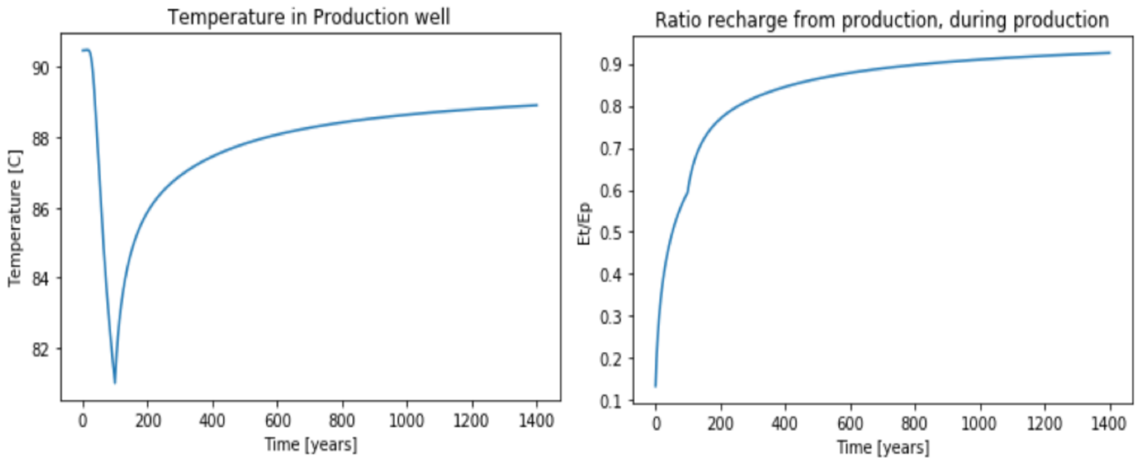


Figure 5.3: Results for a simulation of Base Case with reservoir thickness of 50 meters. In the graph on the left hand side the well temperature is plotted. In the graph on the right hand side, the recharge in the whole reservoir is plotted. During the fist 100 years of this simulation, geothermal energy is produced. The following 1300 years, no production takes place.

	Initial condition	**After 100 years of production**	**100 years after production stops**	**1300 years after production stops**
Well Temperature	90.3 ^{o}C	81.45 ^{o}C	85.8 ^{o}C	88.8 ^{o}C
Recharge Ratio	-	60.0%	76.9%	92.6%

Table 5.3: A summary of the results for a simulation of 1400 years, with production during the first 100 years and recharge during the following 1300 years.

reservoir and over- and under burden decreases. This results in less recharge, and therefore the rate at which the reservoir heats up decreases.

At the end of the simulation the temperature in the reservoir has not returned to its original state. Even though the heating up of the reservoir goes very slowly, the temperature remains increasing and does not flatten out completely during the 1300 years of simulation. But it seems to approach an asymptote that lies lower than the initial reservoir temperature.

The results presented in Figure 5.3, show that a geothermal system is not fully renewable. After 100 years of extraction of the geothermal resource, the temperature in the reservoir has dropped by almost 9 ^{o}C. During a period of 100 years after production has stopped, the temperature in the reservoir recovers half of this decline. And in the 1300 years after the production has stopped, the reservoir has not returned to its original state, but is still recovering. Based on these results it would not be accurate to suggest that geothermal energy is a fully renewable source of energy. However, it is undeniable that a large part of the energy of the reservoir is renewed in a time frame that is of interest. After the production has been shut down for 100 years, almost 77% of all the produced energy has flowed back into the reservoir. This offers opportunities to restart the geothermal production from this reservoir. Because, even though the reservoir does not have the same energy content as before the production started, there still is potential to produce energy from the reservoir. Therefore, we conclude that the renewability of the geothermal resource contributes to the sustainable use of a geothermal system.

6

Discussion

In this chapter we discuss several aspects that should be taken into account when analyzing this study. Section 6.1 discusses the limitations of the scope and its effect on the results. Section 6.2 discusses the effect that an incorrect model setup has. Section 6.3 reflects on a number of conceptual analyses. Section 6.4 assesses the sustainable use of a geothermal system.

6.1. Limitations of the Scope

For the feasibility of this study the scope of research is limited to the sustainable use of geothermal energy in a geothermal system with one doublet. Therefore, only the role that the subsurface plays within a geothermal project is taken into account. In reality many more aspects should be included in the production design and strategy for a geothermal system.

First, is the economic aspect of a geothermal project. During this research the economic costs of a geothermal project are not included when making a production design and strategy. The CAPEX and the OPEX will have an effect on the preferred production design and strategy, and perhaps not every geothermal project is feasible due to the costs.

The second aspect is the circularity of the geothermal project. The amount of materials and energy invested to install and use the geothermal project. The energy required to install the geothermal project and keep it running will affect the net energy output.

The third aspect, is that this research only investigates a geothermal project with one doublet. In reality multiple injecting or producing wells can be installed, in various well patterns. The well design of a geothermal project can have a large influence on the power output of the system.

These three aspects are outside the scope of the research for this thesis, and are therefore not evaluated. When making a production design and strategy for a geothermal project they should definitely be investigated.

6.2. Effect of incorrect model setup

The results obtained during this research are heavily dependent on the model setup and the simulation tool that is used. When making the model setup to simulate the production process, the goal is to chose the initial conditions in a way that the model is in line with reality as much as possible. A change in the initial setup of the model, can have a negative impact on the reliability of the results. It proved to be very important to correctly choose the initial conditions, when making the model setup to simulate the production process. Here we will discuss the effect of not choosing the correct initial values of the following parameters; the initial temperature distribution and the boundary conditions.

First, the initial temperature distribution in the model is determined by the temperature gradient throughout the model. Unlike a sensitivity study executed by Bauer et al., where he used a constant geothermal gradient, the thermal gradient in this model is not linear throughout the whole model. The thermal gradient is dependent on the thermal conductivity, which is not equal in the reservoir and the confining layers. By adjusting the temperature gradient to the thermal conductivities a constant heat flux through the model is obtained (Equation 3.9).

If the model setup had an initial temperature distribution with a constant thermal gradient, but a varying thermal conductivity, the model is not in equilibrium. When the simulation starts, the first reaction of the model is to return to a state with a constant heat flux throughout the model. This means that if the thermal gradient in the reservoir is too large for the corresponding thermal conductivity, heat will start to flow from the reservoir towards the confining layers and vice versa. The flow of heat from the over- and underburden towards the reservoir is monitored as recharge in the model. If, due to an incorrectly imposed thermal gradient, heat is transferred between the confining layers and the reservoir, the monitored thermal recharge is significantly affected. The total amount of recharge ratio can deviate by 30% if the initial temperature distribution is not in equilibrium with a steady state (Appendix D). As a result, the effect that a parameter has on the geothermal production process can be incorrectly assessed. This proves how important it is to make sure that the model is in equilibrium when the simulation starts.

The second aspect of the model setup that has a large impact on the results when chosen incorrectly are the boundary conditions. In this model the top and the base are characterised by a constant temperature boundary. This constant temperature boundary at the bottom of the model simulates a constant heat flux from the centre of the Earth. With a constant temperature boundary at the top of the model, the heat flux flows out of the model towards the surface through the strata overlying the model. This ensures that the model is not gradually heated up by a constant input of heat flux from the bottom. The side boundaries of the model provide an inexhaustible source or sink of water, to maintain the pressure within the model. The grid size of the model is setup in a way that near the boundaries there is minimal effect on the production process. Therefore, they are characterised by a constant temperature. The reason for this is that we assume that the production process will not have effect beyond the boundaries of the model.

6.3. Conceptual Analyses

Influence ratio horizontal vertical permeability

Section 4.4.2 discusses that in the Base Case there is minimal convection from the over- and underburden towards the reservoir. Even when the permeability is increased a thousand times, the convection does not contribute significantly to the thermal recharge. This process is enhanced by the ratio between the vertical and horizontal permeability. With a vertical permeability that is ten times smaller than the horizontal permeability, the vertical convective heat flow is even more limited.

In the reservoir the ratio between vertical and horizontal permeability is the same. As a result, the predominant direction of the convective heat flow is horizontally. Now suppose that the vertical permeability is equal to the horizontal permeability. This causes an increase in vertical convective heat flow. What would be the effect of more vertical convective heat flow to the production process? Although we did not examine what the effect would be, we expect that more heat will be extracted from the over- and underburden. Because more heat can be transported form the boundary between the reservoir and the confining layers. This enhances the thermal recharge and has a positive effect on the production profile.

Asymptotic behaviour

From the results presented in Chapter 4, we have seen that the production profile gradually moves towards an asymptote, e.g. in Figure 4.12b. Analyzing the results, for the various experiments conducted for this research we expect that this well temperature asymptote will lie between 60^oC and 55^oC. Figure 4.12b shows that the temperature of the asymptote depends on the production rate, a higher production rate results in a lower asymptotic well temperature. The production rate is one parameter that causes a small deviation in the temperature of the asymptote. The fact that a production parameter has an effect on the temperature of the asymptote, makes it very plausible that the asymptote is dependent, on more parameters to a greater or lesser extent. The question remains, what other parameters determine the temperature of the asymptote.

We expect that the injection temperature is a parameter that has a large influence on the temperature of the asymptote. When the well temperature starts to approach the asymptote, the produced water is a mixture of cold water that has been injected and hot water coming from the reservoir in the opposite direction of the injection well. If the well temperature approaches the asymptote, i.e. reaches a steady state, the production temperature will have found a balance in extracting part injected water and part water originated from different directions of the reservoir. Assume that the asymptote lies as 55^oC, with an initial reservoir temperature of 90^oC and a injection temperature of 35^oC. Roughly speaking, the asymptotic temperature consists of one third initial reservoir temperature and two thirds injection temperature. When it is assumed that this is how the steady state production temperature reacts to the injection temperature, it means that the injection temperature has a large impact on the temperature of the asymptote.

In addition to from the effect that the injection temperature has on the asymptote, we assume that the parameters examined during this study also have an impact on the temperature of the asymptote.

Especially the effect on the amount of recharge will have an impact. Thermal recharge heats up the injected water when it moves from the injector to the producing well. More recharge results in a higher temperature of injected water when it reaches the producing well. This will have a positive effect on the well temperature asymptote, i.e. more thermal recharge causes a higher asymptote. Therefore, we expect that all the parameters that have a positive effect on the thermal recharge, will cause an increase in the temperature of the asymptote. Because these expectations are only based on a back of the envelope calculation, further research to investigate the effect of the injection temperature would be very interesting.

6.4. Assessing the sustainability

Sustainability is a much discussed topic these days. However, the concept of sustainability is subject to a lot of interpretation. The definition of sustainable development, given in Section 2.4, is a very broad understanding and not specifically useful for the development of a geothermal system.
To be able to determine how to produce sustainably from a geothermal system, it should be determined what sustainable development of a geothermal reservoir means. This section discusses the following three points to make a deliberate choice on how to use a geothermal system sustainably; the need for geothermal energy as a source of energy; the possibility to produce at an asymptotic well temperature; and the effect of renewability of the resource.

Need for Geothermal energy

The first point of discussion is the need for geothermal energy. It can be learned from history that the source of energy can change rapidly. For example, in the past 150 years of energy consumption, the main sources of energy has shifted from biofluels to coal and later to oil and gas. These days the world focuses on renewable energy sources (Salvador, 2005). Following this trend, the need for geothermal energy might not last as long as one might think. Therefore, it might not be essential to design a production plan where the production can continue for multiple centuries.

Asymptotic well temperature

The second point of discussion that should be taken into consideration, is the asymptotic behaviour of the well temperature. When the well temperature approaches the asymptote, the geothermal production reaches a steady state. Figure 6.1 gives a schematic overview of the temperature progression in a geothermal reservoir, and the different stages it goes through. The temperature is plotted against a unitless time. The letters A, B & C indicate the different stages during geothermal production, and the letters D & E indicate the stages after production has stopped.
The letter A represents the first stage, the constant production at initial reservoir temperature. This stage ends when thermal break-through occurs. The power output during this stage is maximum. The length of this stage depends strongly on the reservoir thickness, the production rate and well spacing.
The letter B represents the stage with a decreasing well temperature. During this stage the well temperature drops from the initial reservoir temperature to the asymptotic well temperature. The rate at which this happens, is dependent on the production design and strategy.
The letter C represents the stage when the well temperature approaches the asymptote. The asymptote is represented by the dashed line number one. When the temperature approaches the asymptote, the geothermal system is in a steady state. If the steady state is reached, the production with the same output can continue for an infinite amount of time. When this happens, the production at the asymptotic well temperature is 100% sustainable. To be able to achieve this, the following two controlling factors should be considered.

The first factor is the design of the system installed at the surface. This plays an important role in the lifetime of the whole geothermal system. This determines the range of production temperatures the system can process. When the system has a larger range, it can process geothermal water with a lower temperature. That means that after thermal break-through the system can continue to produce for a longer time. In order for a geothermal system to be developed in a sustainable way, the project design should be able to handle water with the asymptotic well temperature, to ensure that the system keeps functioning when a steady state temperature is reached.

The second factor is energy demand. The easiest way to produce sustainable and minimize the well temperature decrease, is to maintain a low production rate. However, producing at a low rate results in a low energy output. Because the objective of geothermal extraction is to produce energy, the

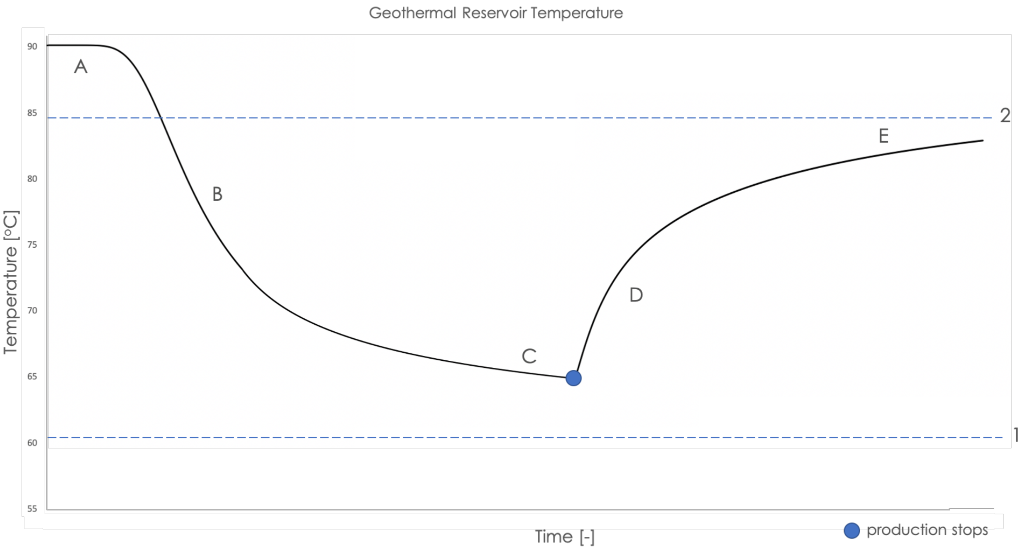


Figure 6.1: A schematic overview of the temperature progression in a geothermal system, during and after production has stopped.

purpose of the extraction is lost when the output is very low. Therefore, it might be a better option to produce at a rate at which the present energy demand is met. As a result, the well temperature will drop and might at some point reach the asymptote. For this scenario it is important to take expected technical developments into account when discussing the sustainable use of a geothermal system. With technical developments the energy demand might decrease in the future, due to better isolation of buildings, a more efficient way to transfer the heat and a more efficient way to use the energy extracted from the heat. In the time it takes for the well temperature to reach the asymptote, the techniques might be developed in a way that the heat provided by the asymptotic well temperature is sufficient to meet the energy demand of that time.

The production could continue for an indefinite amount of time if it is possible to reconcile production at the asymptotic well temperature with the system at the surface and future energy demand.

Renewability of a geothermal system.

The third point of discussion that should be taken into consideration when determining a sustainable use of a geothermal system, is the renewability of the resource. After production stops, a geothermal system has the ability to be recharged, and therefore to return to a greater or lesser extent to its original state. When the geothermal system recharges, the temperature in the reservoir increases. Figure 6.1 presents the temperature progression in the reservoir, after production has stopped. The letters D & E represent the different stages of recharge.
The letter D represents the stage when the rate of thermal recharge is high. Directly after production has stopped, the temperature difference between the geothermal system and its surrounding is large. Because a large temperature difference stimulates the thermal recharge, during the first stage of renewability the rate of the recharge process is high.
When the reservoir temperature increases, the thermal recharge decreases and the renewal of the geothermal system slows down. Letter E indicates the stage when the thermal recharge rate is low and starting to approach an asymptote. With the results of this study, we cannot give a definite answer whether or not the geothermal system will completely return to its original state. In the timescale that we have studied during this research, the temperature in the reservoir will move to an asymptote that seems to have a lower temperature than the initial reservoir temperature. In Figure 6.1 indicates this asymptote by the dashed line number two. When this asymptote lies lower than the initial reservoir temperature, we assume that a geothermal system is not completely renewable in the timescale that is of interest to the current developments.

When discussing the renewability of a geothermal system, we should also put it into perspective with other sources of energy. Figure 6.2 displays the recharge time of a number of energy sources on a logarithmic timeline. To examine where geothermal energy fits into the timescale of renewability
The first resources on the timeline are Solar and Wind energy. These two are both inexhaustible resources. During the production of wind and solar power, the resources are constantly and immediately renewed. Therefore, the recharge time is instant and these resources are completely renewable.

Second on the timeline is energy from biomass, e.g. a tree. After a tree has been cut down, it takes years or decades before the tree has returned to its original state. While the time it takes to cut down a tree and use it as an energy source, is a matter of days. The tree itself is completely renewable, but the timescale is in a different order of magnitude than the production time.
The resources with the largest recharge time are fossil fuels. The formation of oil and gas takes million of years. Dependent on the size of the timescale, one could argue that fossil fuels are renewable. However, on a human time scale fossil fuels are not renewable.
This raises the question where geothermal energy fits into this time scale? We consider geothermal energy to be in the same category as biomass. Even though the geothermal system is recharged during production, it might take centuries before it has returned to its original state. Therefore, we conclude that a geothermal system is for a significant part renewable on a timescale that is of interest to human development, but not completely. Nevertheless, it is an important contribution to the sustainable use of a geothermal system.

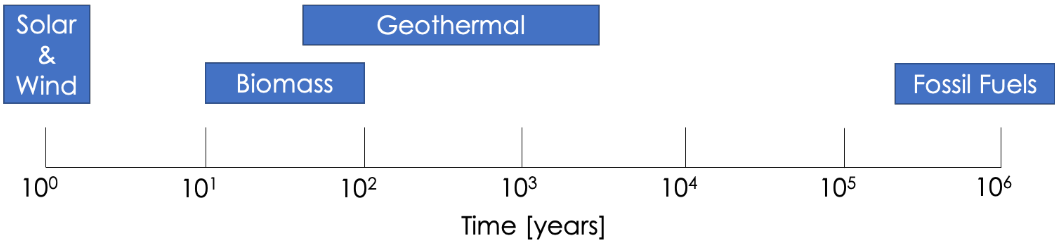


Figure 6.2: A schematic overview of the recharge time for a number of difference energy resources.

After discussing the need for geothermal energy as a source of energy, the possibility to produce at an asymptotic well temperature, and the effect of renewability of the resource, we can now define what sustainable use of a geothermal system means. When a geothermal project begins and energy is extracted from a geothermal system, the well temperature will drop. With an optimisation of the production design and strategy and favourable geological parameters this process can be stretched out for a longer period of time. A slower decrease of the well temperature enhances the sustainability of a geothermal project. Even though part of the extracted energy will be recharged towards the system when production stops, the energy extracted in stage A and B (Figure 6.1) causes a decrease in well temperature and therefore this part of the production period is not sustainable.
When the well temperature reaches the asymptote the geothermal system is in a steady state. This means that the output will not decrease and that the production is completely sustainable.
We conclude that, during the production between initial temperature and asymptotic well temperature, the system is not used sustainably. Although the sustainability can be enhanced with the right production design and strategy. But, when producing at the asymptotic well temperature, the energy extracted from the geothermal system is sustainable.

All of the results presented in this thesis results emphasize the large potential of a geothermal system. The phenomenon of thermal recharge has a large impact on the enhancement of the production profile. The positive effect plays an important role in the sustainable use of a geothermal system. This study shows that thermal recharge makes it possible for a geothermal system to produce for decades and in some cases for centuries. And if it appears that the well temperature will approach an asymptote, and that the production will reach a steady state, the production from a geothermal system could continue for an infinite amount of time. With that, the definition of the World Commission on Environment and Development (1988) that sustainable development should meet the need of the present without compromising the ability of future generations to meet their own needs, is satisfied.

7

Limitations & Recommendations

This chapter discusses the limitations of this research. Subsequently, we provide recommendations for further research.

7.1. Limitations

During this research we encountered a number of limitations; the oversimplified geology of the model; the pressure in the reservoir; the temperature gradient; and the in situ measurements. This section will elaborate on these limitations.

Oversimplified geology

The model used for this research is a highly simplified representation of a completely homogeneous geothermal reservoir. In reality the properties of a geothermal reservoir are much more heterogeneous. This model is a oversimplified representation of the subsurface, and consequently the results obtained during this study will differ from the outcomes in practice. In the Section 7.2 we give a number of recommendations on how to implement more heterogeneity into the model, in order to make it a better representation of the reality.

Pressure

During this research, the examination of the effect of a change in pressure in the reservoir is minimal. We have checked that pressure surrounding the injection well is always within the range of the SODM norm (SodM en TNO-AGE, 2013) for every tested case. However, when simulating the production process, the production rate is imposed to the wells. Therefore, the well will produce at this rate, and is not affected by the pressure this causes. This became clear when examining the effect of difference in permeability in the reservoir. It turned out that this did not have any effect on the production rate. Merely on the pressure in the reservoir. Further research should include the pressure buildup in the reservoir when examining the production process.

Temperature gradient

To examine the effect of the thermal conductivity, that geological property was either changed for the reservoir of the confining layers. When changing the thermal conductivity, the temperature gradient in that area changes as well, in order to obtain a constant heat flux throughout the whole model.
By changing the temperature gradient in the reservoir, the energy content changes as well. To minimize this effect, the average reservoir temperature was kept constant. However, the rate of temperature decline is affected by this difference in temperature variation in the reservoir.
Therefore, it is more difficult to compare the results of the effect of the change in thermal conductivity in the reservoir.

Measured in situ

The results presented in this research concerning the well temperature are all in situ measurements. By bringing it to the surface the results could prove different. In addition, when calculating the energy output, the loss that will be encountered due to the heat exchanger, is not taken into account. Therefore, the energy outputs will prove to be lower in reality.

7.2. Recommendations

This section provides recommendations for future research. The first recommendation concerns broadening the scope of the research by making the model more true to nature and examining the effect of more parameters and a case study. The second recommendation concerns the asymptotic behaviour of the well temperature.

The first recommendation is to make the model a better representation of the subsurface, and with that, test the effect of more parameters. In Section 7.1 we indicate that one of the limitations of this research is the oversimplification of the model. When further research is done on the effect of geological uncertainties on the sustainable use of a geothermal system, it is recommended to implement more heterogeneity into the model in forms of; Net-to-Gross; fractures; faults, both sealing and non-sealing; horizontal variations in reservoir thickness; variation in the vertical to horizontal permeability ratio. As a result this will contribute to a better representation of the subsurface, and the effect of these parameters on the production profile can be examined. In addition the pressure build up in the reservoir during production should be monitored

In addition to the recommended geological uncertainties, it is recommended to also test the effect of other production parameters to the production profile such as; well orientation; multiple doublets; perforation strategy, e.g. inject at the bottom of the reservoir and produce at the top of the reservoir; varying off-take to anticipate the changing energy demand throughout the year; injection temperature. We also recommend to make a more detailed well simulation, to control the pressure build up in the well. With analyzing more production parameters, an improved production design and strategy can be made to sustainably use the geothermal system.

Subsequently, we recommend that further research investigates a case study. This means that the simulation of a geothermal project will be executed using a model that is representative for an existing geothermal reservoir. The obtained results will give a better insight into what can be expected when a geothermal project is installed in practice. For the case study, the economic part of a geothermal project should also be taken into account. The economics of a project might have an influence on the choices for the optimal production design and strategy.

The second recommendation concerns the asymptotic behaviour of the well temperature. In this thesis we express our expectations regarding the factors that have an influence on temperature of the asymptote, and whether or not the geothermal production will reach a steady state. Future research should extensively examine the behaviour of the asymptote to check whether these expectations are correct and if a steady state production can be reached.

8

Conclusion

The objective of this study was to investigate under what conditions a geothermal system is used sustainably. In order to find out whether geothermal energy could be part of the solution for the energy transition.

In this chapter, the conclusions to the three research questions are presented.

- **What are the effects of geological uncertainties on the geothermal production profile?**

The two geological uncertainties that have the largest impact on the production profile are the reservoir thickness and the confining layers. The effect of one of these two parameters is very dependent on the other parameter. The results presented in this study clearly show that the confining layers have a large impact on the geothermal production profile due to thermal recharge. The effect of the confining layers increases with a decrease in reservoir thickness. Therefore, the effect of geological uncertainties in the over- and underburden have a larger impact for a thinner reservoir. On the other hand, when the reservoir is thicker the effect of geological uncertainties of the reservoir have more effect.

- **What are the effects of production parameters on the geothermal production profile**

The production rate is the parameter that has the largest impact on the production profile. A lower production rate results in more thermal recharge per produced energy and therefore the well temperature decline is lower. On the other hand, producing at a lower rate gives less energy output per time unit.

An increase in well spacing enhances the recharge ratio and therefore decreases the drop in well temperature. The pressure difference between the wells enhances the velocity of the movement of the cold front for a shorter well distance. A larger well spacing has a positive effect on the sustainable use of a geothermal system.

- **How can the effect of the geological uncertainties and production parameters be translated to a sustainable production design and strategy?**

The most sustainable production strategy is to maintain a low production rate and a large well spacing. However, by doing this it is likely that the demand for energy cannot be fed. Therefore, a production strategy should be designed with the right balance between sustainability and energy output should be found, depending on the geology of the reservoir.

The following two rules of thumb apply when making a production strategy: First, with a doubling of the reservoir thickness, the production rate can be increased by approx. 50%.

Secondly, with an increase of well spacing of 20%, the production rate can be increased by approx. 50%.

Subsequently, we emphasize the positive effect that thermal recharge from the confining layers towards the reservoir has on the production profile. This phenomenon plays an important role in the sustainable use of a geothermal system. This study shows that with the correct production design and strategy the lifetime of a geothermal project can be enhanced. As a result the geothermal system is used sustainably and the geothermal production can continue for generations to come.

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Appendices

A

Grid Size Check

Section 3.4.5 discusses the importance of the correct grid size. With a grid size too large, simulations can be inaccurate. With a smaller mesh, the computation time increases. It is essential to choose the right grid size.

To check whether the grid size that is being worked with is accurate enough, a simulation with smaller cell sizes was executed. The size of every cell, was half of the size in every direction, of the cells used in the Base Case. The dimensions of the model remained the same, therefore the model contained eight times more cells than the Base Case. As a result, the computational speed decreased, and the simulation took so long, that it was unpractical to simulate for 300 years. Therefore, only the first 100 years were simulated.

The results of this model, and of the base case can be seen in the Figure A.1

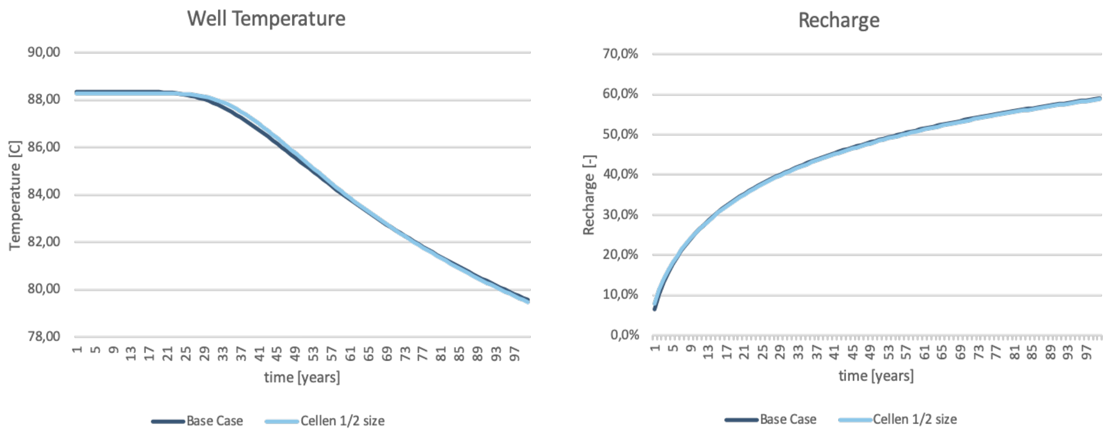

Figure A.1: The dark blue line represents the base case with a grid size discussed in Section 3.4.5, the light blue line represents a simulation using cells with half the dimensions of the 'Base Case'.

It is clear from fig A.1 that the results of both cases are almost similar. Therefore, the preferred grid size is the Base Case, due to the shorter computational time.

Figure A.2 shows what the effect is of a change in grid size of the over- and under burden to the well temperature and the recharge ratio. For the Base Case simulation, the over- and under burden both consists of 18 vertical cells, with a thickness of 10 meters close to the reservoir and 100 meters at a proper distance of the reservoir, the outer cell has a thickness of 10 meters to minimize the effect of the boundary conditions. In the model with the 'large grid size confining layers', the over- and under burden consist of 3 vertical cells each, 2 cells with a thickness of 400 meters, and a boundary cell of 10 meters thick.

Figure A.2 shows that an large grid size in the over- and underburden causes a significant change in the production profile. Due to the incorrect grid size, the amount of thermal recharge decreases drastically. As a result the well temperature decreases more than in the Base Case. The results indicate that when the grid size is too large, the obtained results will be incorrect.

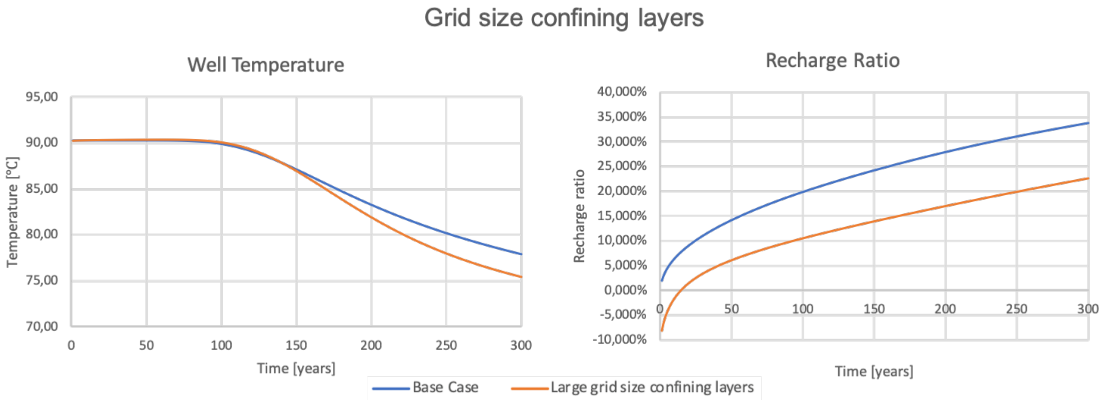

Figure A.2: The well temperature and the recharge ratio during 300 years of production from a reservoir of 200 meters thick. The Base Case consists of 18 vertical cells in the over- and under burden. The 'large grid size' consists of 3 vertical cells in the over- and under burden.

B

Effect of well perforation strategy

Section 4.8.2 discusses the importance of choosing the correct well design. But choosing the right well distance is not the only choice that has to be made concerning the wells. The perforation strategy will also have impact on the production profile.

Figure B.1 shows what the effect is of a difference in well perforation strategy. In the Base Case, the well is perforated along the entire thickness of the reservoir, the 'half perforated' case, the well is perforated over a thickness of 50 meters in the middle of the reservoir.

The most striking difference in recharge ratio between the two cases occurs right at the start of the production. In the Base Case the recharge ratio commences at almost 2% and from there, the graph rapidly increases. In the model where the well is only perforated along 50 meters, there is almost no recharge in the first years of production. After 10 years, the recharge ratio is less than 1%.

This difference can be explained by looking at Figure B.2, which shows the temperature distribution in the reservoir after 10 years of production. In the Base Case, the cold front is distributed along the entire thickness of the reservoir, reaching the boundaries with the over- and under burden. In the half perforated case, the cold front moves primarily in the direction of the production well, but also slowly in the vertical direction. After 10 years, the cold front arrives at the boundary between the reservoir and the over- and under burden, making it possible for recharge to occur due to the temperature difference.

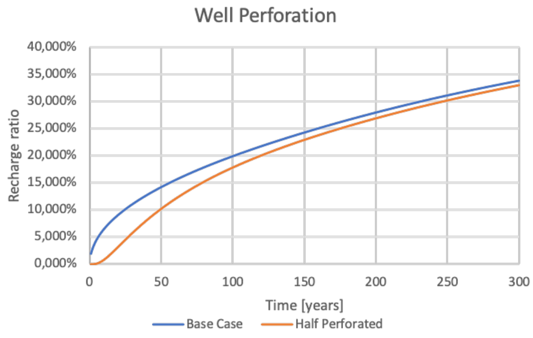

Figure B.1: The effect of the well perforation on the recharge.

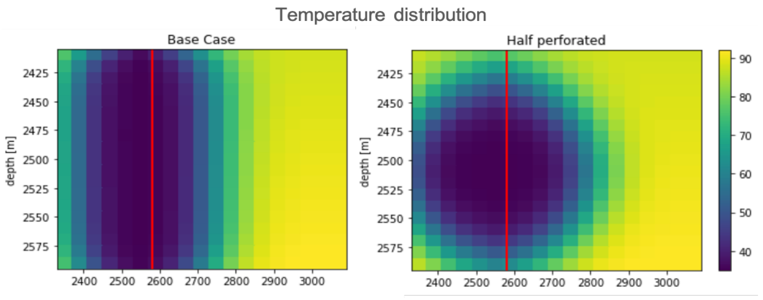

Figure B.2: The temperature distribution in a reservoir of 200 meters thick after 10 years of production. The Base Case represents the model where the well is perforated along the entire thickness of the reservoir. In the half perforated case, the well is perforated along 50 meters in the middle of the reservoir.

From Figure B.1 and B.2 it can be concluded that a well that is perforated along the entire length of the reservoir improves the recharge. Which will subsequently improve the production profile and therefore the sustainability of the reservoir. Therefore, when making a production plan, the well should always be perforated along the entire thickness of the reservoir.

C

Results

C.1. Thermal Conductivity of the reservoir

Figure C.1 and Figure C.2 show the decline in production temperature and the recharge ratio for respectively a 50 meter and a 200 meter thick reservoir. The figures show the results for reservoirs with a rock thermal conductivity (λ_{rs}) of 1.5, 3 and 5 [W/m/K], the middle is considered to be the Base Case.

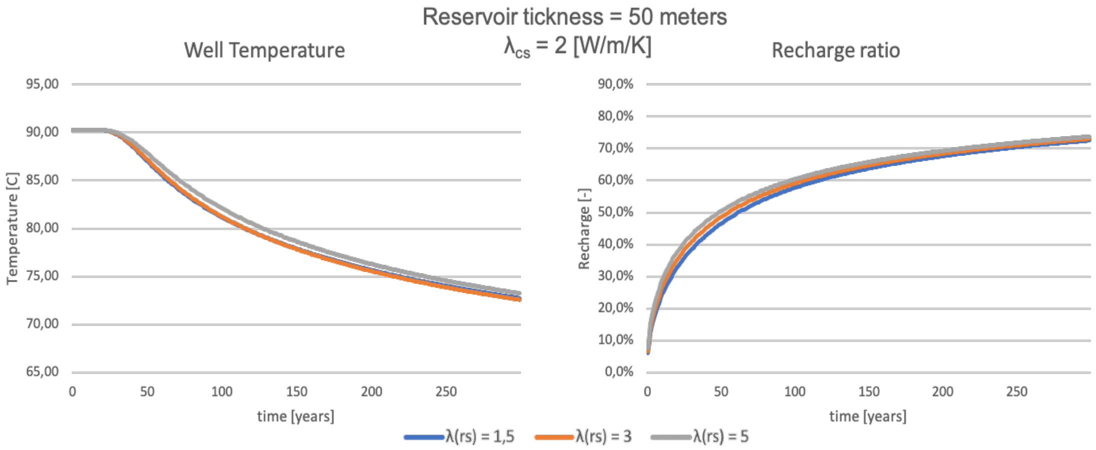

Figure C.1: The sensitivity of the production temperature and recharge ratio to change in thermal conductivity of the reservoir rock, simulated for a period of 300 years. Explanation as in Figure 4.1. The blue, orange and grey line represent a thermal conductivity of the reservoir rock (λ_{rs} of respectively 1.5, 3 and 5 [W/m/K].

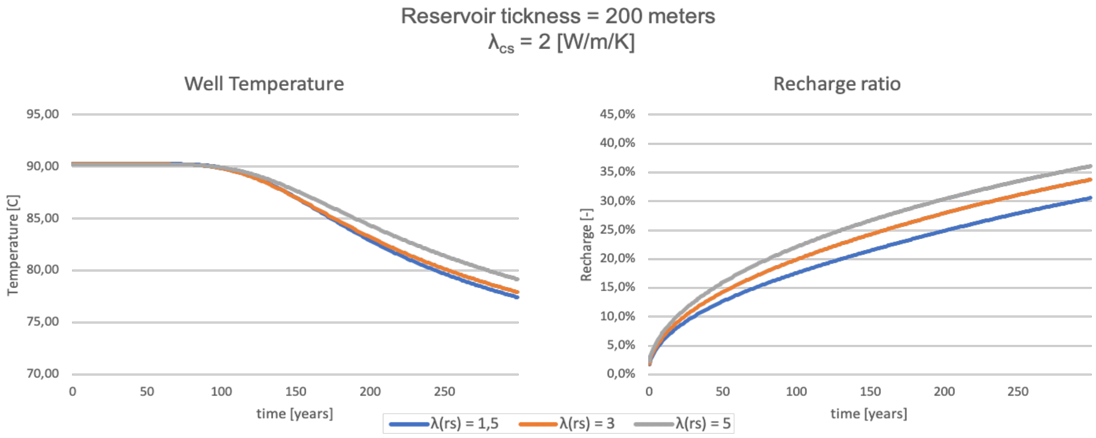

Figure C.2: The sensitivity of the production temperature and recharge ratio to change in thermal conductivity of the reservoir rock, simulated for a period of 300 years. Explanation as in Figure 4.1. The blue, orange and grey line represent a thermal conductivity of the reservoir rock (λ_{rs} of respectively 1.5, 3 and 5 [W/m/K].

C.2. Thermal Conductivity of the confining layers

Figure C.3 and Figure C.4 show the decline in production temperature and the recharge ratio for respectively a 50 meter and a 200 meter thick reservoir. The figures show the results for models with thermal conductivity of the matrix of the confining layers (λ_{cs}) of 0.8, 2 and 3.5 [W/m/K], the middle (λ_{cs}= 2 W/m/K)is considered to be the Base Case.

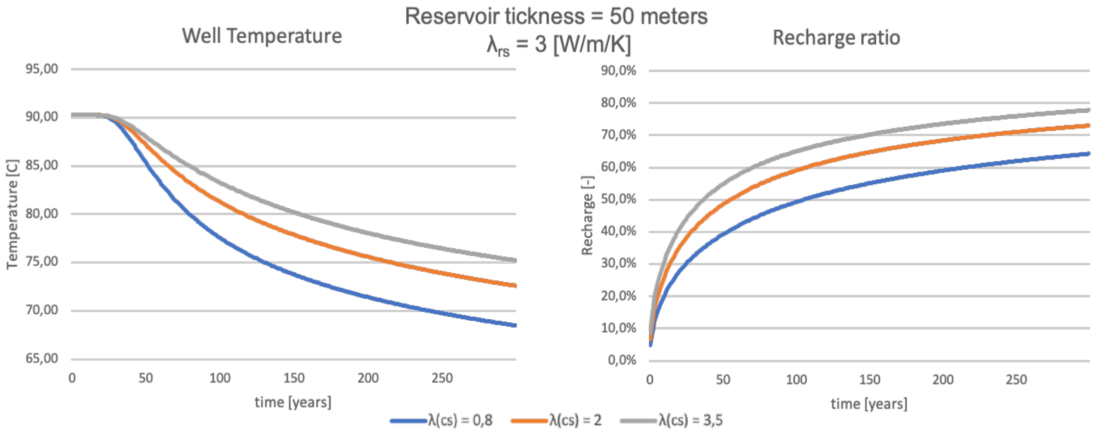

Figure C.3: The sensitivity of the production temperature and recharge ratio to change in thermal conductivity of the matrix of the confining layers, simulated for a period of 300 years. Explanation as in Figure 4.1. The blue, orange and grey line represent a thermal conductivity (λ_{cs} of respectively 0.8, 2 and 3.5 [W/m/K].

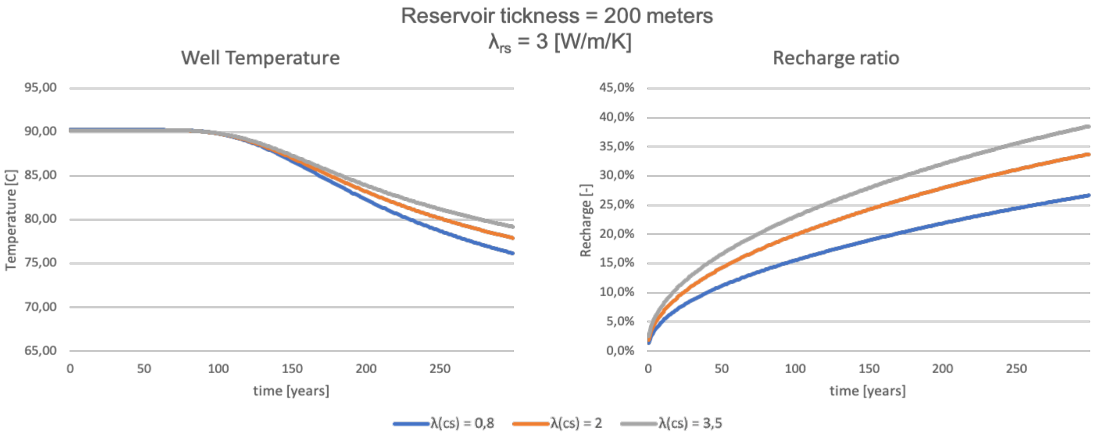

Figure C.4: The sensitivity of the production temperature and recharge ratio to change in thermal conductivity of the matrix of the confining layers, simulated for a period of 300 years. Explanation as in Figure 4.1. The blue, orange and grey line represent a thermal conductivity (λ_{cs} of respectively 0.8, 2 and 3.5 [W/m/K].

C.2.1. Unequal thermal conductivity in the confining layers

Figure C.5 and Figure C.6 show the decline in production temperature and the recharge ratio for respectively a 50 meter and a 200 meter thick reservoir. The figures show the results for the Base Case and two cases where either the overburden has a thermal conductivity of 0.8 W/m/K and the underburden has a thermal conductivity of 3.5 W/m/K or vice versa.

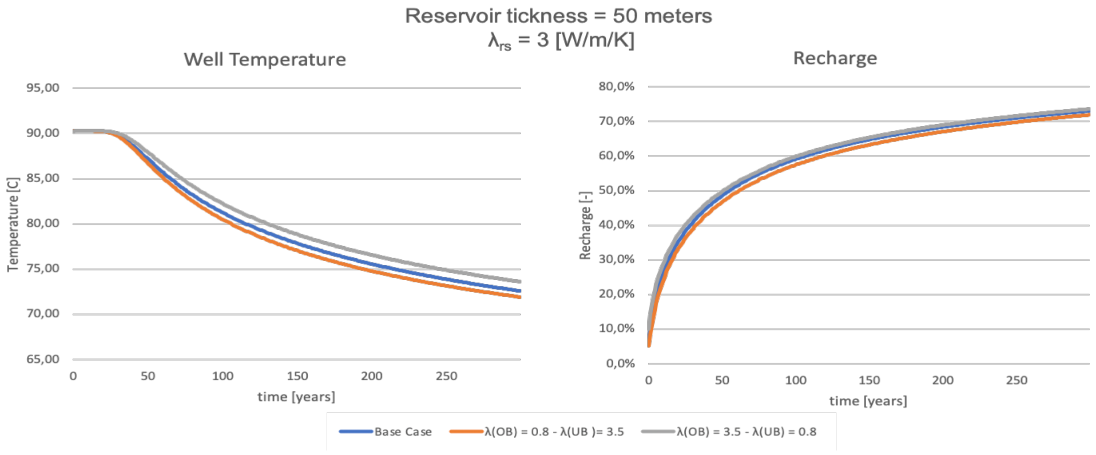

Figure C.5: The sensitivity of the production temperature and recharge ratio to a different thermal conductivity in the over- and underburden, simulated over a period of 300 years for a 50 meters thick reservoir. Explanation as in Figure 4.1. The blue line represents the Base Case. The orange line represents a case with a thermal conductivity of 0.8 [W/m/K] in the overburden and 3.5 [W/m/K] in the underburden. The grey line represents a case with a thermal conductivity of 3.5 [W/m/K] in the overburden and 0.8 [W/m/K] in the underburden.

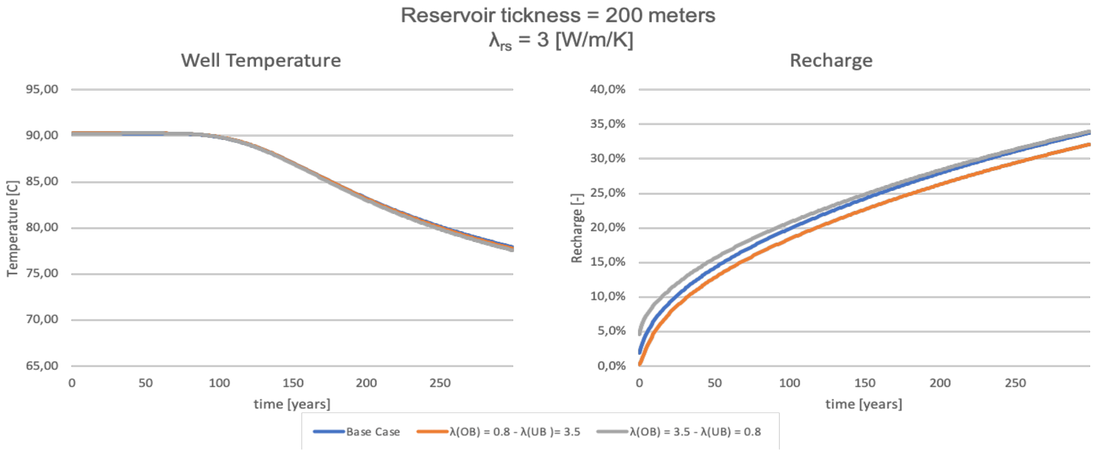

Figure C.6: The sensitivity of the production temperature and recharge ratio to a different thermal conductivity in the over- and underburden, simulated over a period of 300 years for a 200 meters thick reservoir. Explanation as in Figure 4.1. The blue line represents the Base Case. The orange line represents a case with a thermal conductivity of 0.8 [W/m/K] in the overburden and 3.5 [W/m/K] in the underburden. The grey line represents a case with a thermal conductivity of 3.5 [W/m/K] in the overburden and 0.8 [W/m/K] in the underburden.

C.3. Permeability of the confining layers

Figure C.7, Figure C.8 and Figure C.9 show the decline in production temperature and the recharge ratio for respectively a 50 meter and a 200 meter thick reservoir. The figures show the results for models with a permeability of the confining layers of 0.01, 10, and 100 mD, the first is considered to be the Base Case.

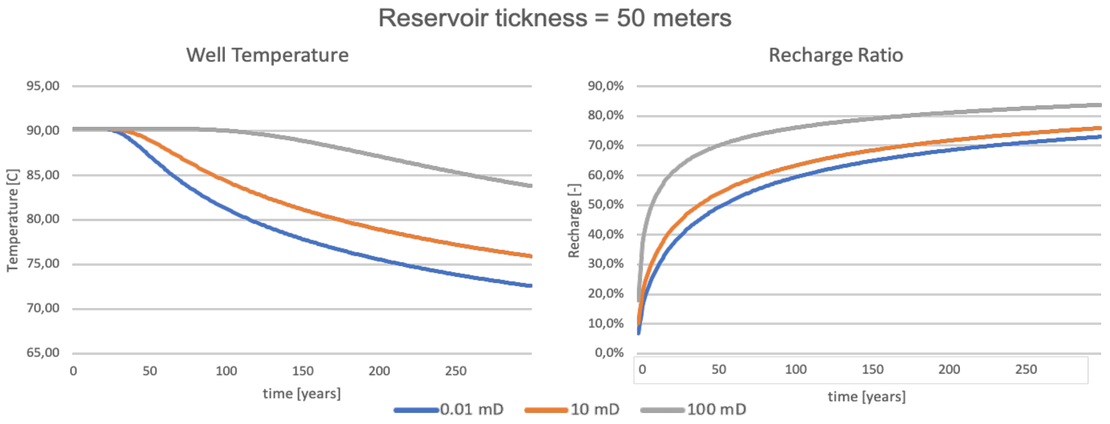

Figure C.7: The sensitivity of the production temperature and recharge ratio to change in permeability of the confining layers, with a reservoir of 50 meters thick. Explanation as in Figure 4.1. The blue, orange and grey line represent a permeability of the confining layers of respectively 0.01, 10, and 100 mD.

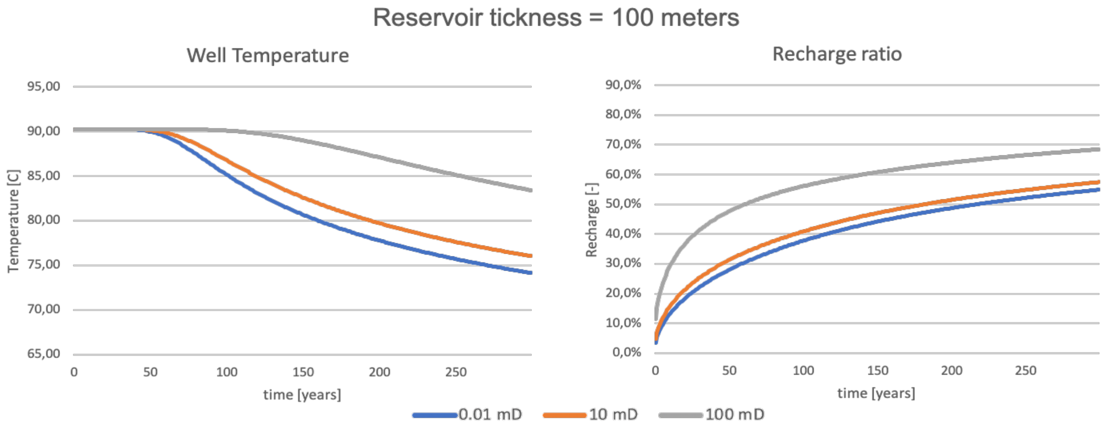

Figure C.8: The sensitivity of the production temperature and recharge ratio to change in thermal conductivity of the matrix of the confining layers, with a reservoir of 100 meters thick. Explanation as in Figure 4.1. The blue, orange and grey line represent a permeability of the confining layers of respectively 0.01, 10, and 100 mD.

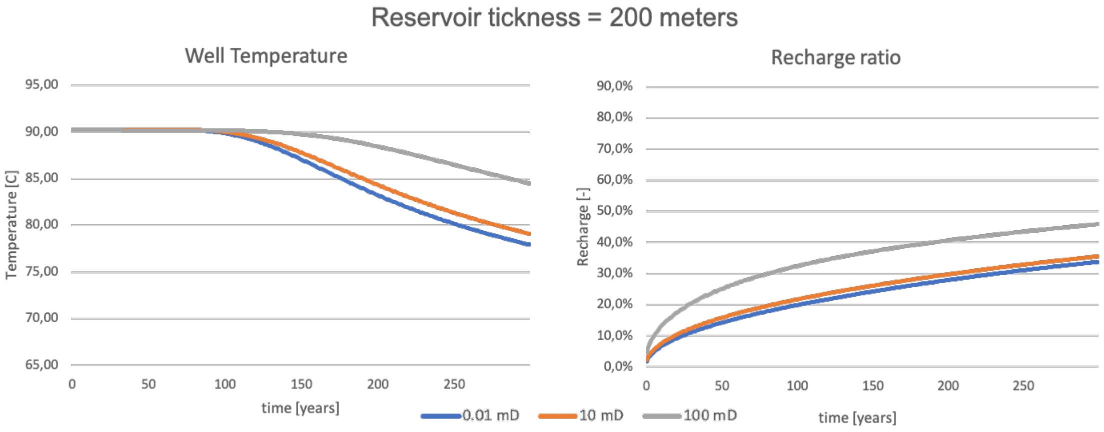

Figure C.9: The sensitivity of the production temperature and recharge ratio to change in thermal conductivity of the matrix of the confining layers, with a reservoir of 200 meters thick. Explanation as in Figure 4.1. The blue, orange and grey line represent a permeability of the confining layers of respectively 0.01, 10, and 100 mD.

C.3.1. Small Permeability

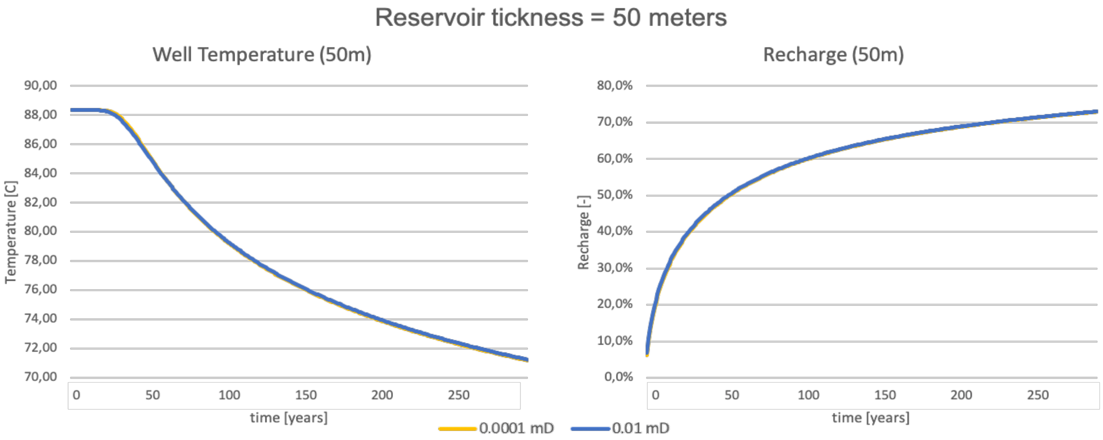

Figure C.10: Effect on the well temperature and recharge ratio when modelled with a permeability in the confining layers smaller than the Base Case, for a reservoir of 50 meters thick.

C.3.2. Unequal permeability in the confining layers

Figure C.11 and Figure C.12 show the decline in production temperature and the recharge ratio for respectively a 50 meter and a 200 meter thick reservoir. The figures show the results for the Base Case and two cases where either the overburden or the underburden has a permeability of 10 mD while the opposite layer has a permeability of 0.01 mD.

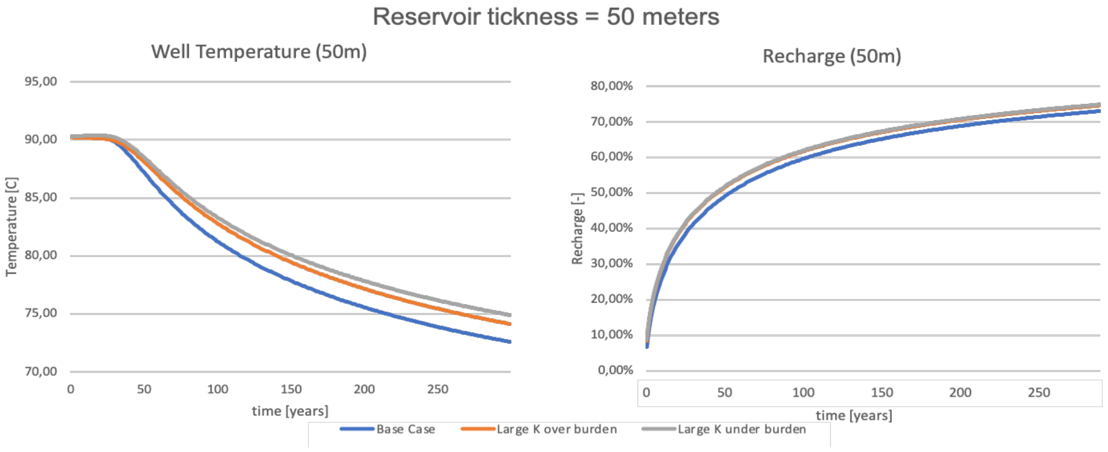

Figure C.11: The sensitivity of the production temperature and recharge ratio to a difference in permeability in the over- and underburden, with a reservoir of 50 meters thick. Explanation as in Figure 4.1. The blue represents the Base Case. The orange line represents the case with a large permeability (10 mD) in the overburden and grey line represents the case with a large permeability (10 mD) in the underburden.

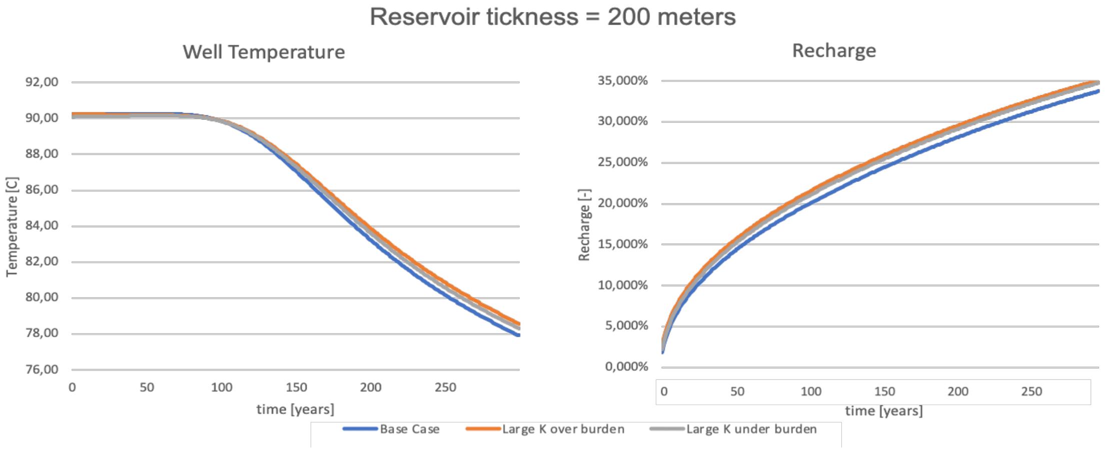

Figure C.12: The sensitivity of the production temperature and recharge ratio to a difference in permeability in the over- and underburden, with a reservoir of 200 meters thick. Explanation as in Figure 4.1. The blue represents the Base Case. The orange line represents the case with a large permeability (10 mD) in the overburden and grey line represents the case with a large permeability (10 mD) in the underburden.

C.4. Production Rate

The graphs in Figure C.13 show the decline in production temperature and the recharge ratio for a 200 meters thick reservoir with a production rate of 150, 250, 400 and 600 m^3/hr.

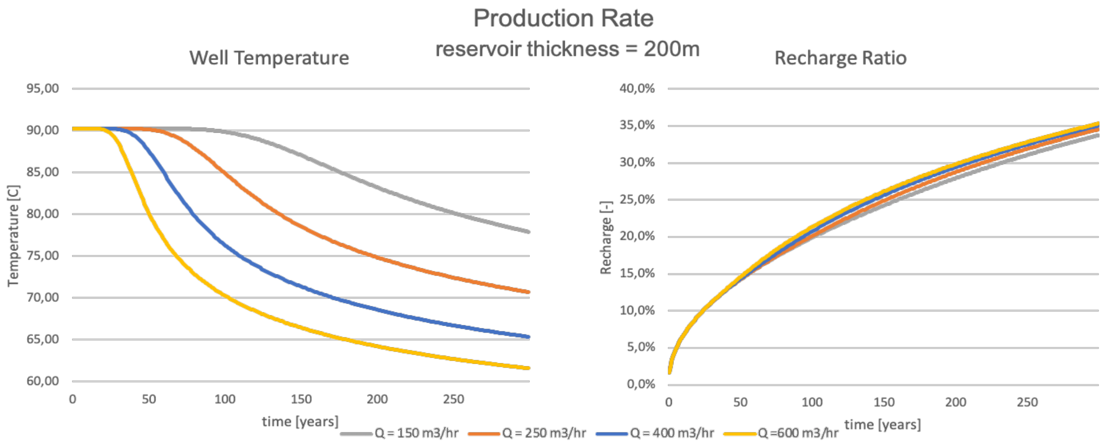

Figure C.13: The sensitivity of the production temperature and recharge ratio to change in production rate, with a reservoir of 200 meters thick. Explanation as in Figure 4.1. The grey, yellow, orange and blue line represent a production rate of respectively 50, 250, 400 and 600 m^3/hr.

The graphs in Figure C.14 show the decline in production temperature and the recharge ratio for a reservoir with thickness of 50, 100 and 200 meters with a production rate of respectively 150, 300 and 600 m^3/hr.

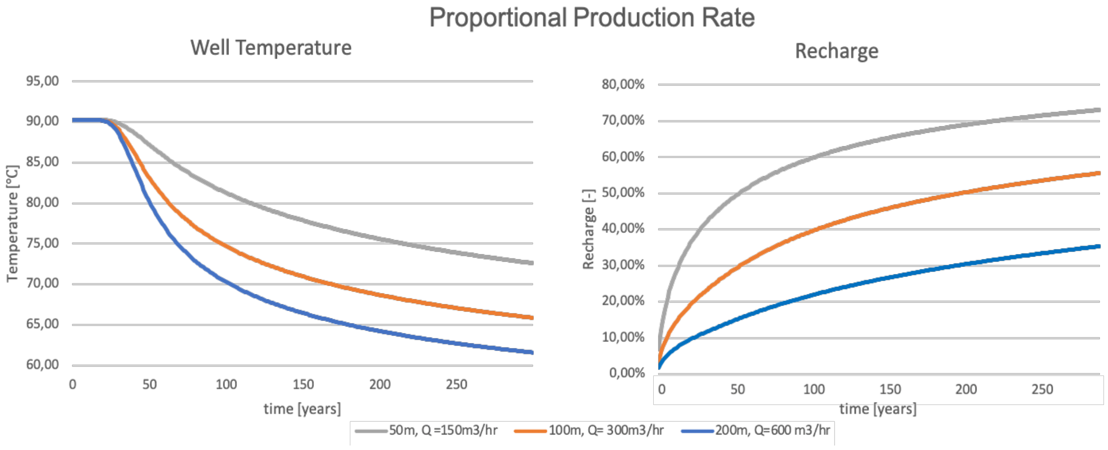

Figure C.14: The production temperature and recharge ratio for three reservoirs of different thicknesses with proportional production rate. Explanation as in Figure 4.1. The grey line represent a reservoir of 50 meters thick with a production rate of 150 m^3/hr, the orange line represent a reservoir of 100 meters thick with a production rate of 300 m^3/h, and the blue line represent a reservoir of 200 meters thick with a production rate of 600 m^3/h.

C.5. Well Spacing

Figure C.15 and Figure C.16 show the decline in production temperature and the recharge ratio for respectively a 50 meter and a 200 meter thick reservoir. The figures show the results for models with well spacing of 1000 m, 1200 m, 1500 m, 2000 m. The model with a well spacing of 1200 is considered to be the Base Case.

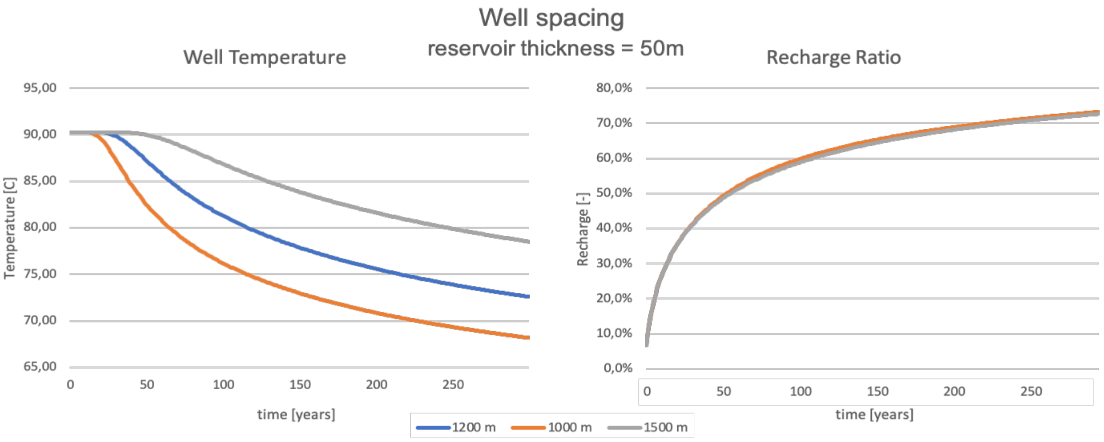

Figure C.15: The sensitivity of the production temperature and recharge ratio to change in well spacing, simulated for a period of 300 years. Explanation as in Figure 4.1. The orange, blue, grey and yellow line represent a well spacing of respectively 1000, 1200, 1500 and 2000 meters.

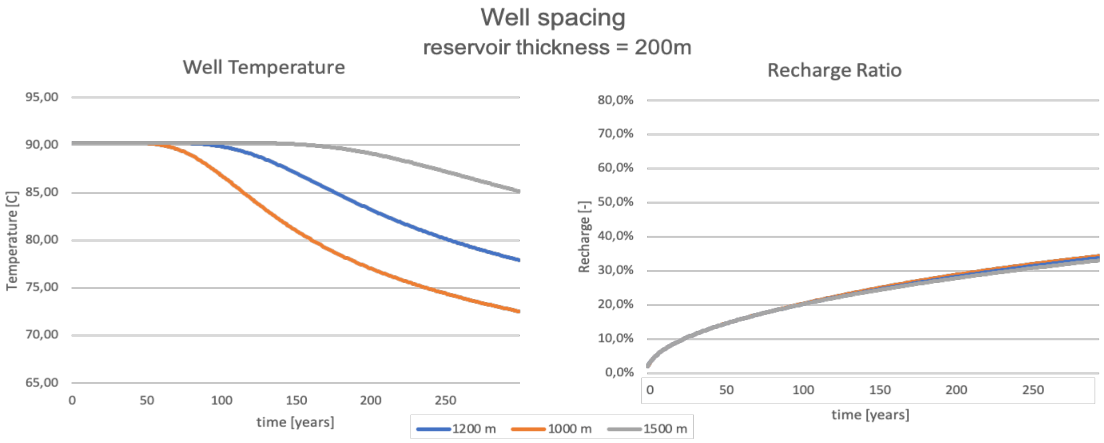

Figure C.16: The sensitivity of the production temperature and recharge ratio to change in well spacing, simulated for a period of 300 years. Explanation as in Figure 4.1. The orange, blue, grey and yellow line represent a well spacing of respectively 1000, 1200, 1500 and 2000 meters.

D

Effect of the Temperature Gradient

Initial temperature distribution is very important. This is achieved by choosing the correct thermal gradient for the corresponding thermal conductivity. With this a constant heat flux throughout the whole model is ensured. Figure D.1 shows what happens if the initial temperature distribution of the model does not ensure a constant heat flux.

Figure D.1 shows the recharge ratio for a scenario where the thermal conductivity of the overburden (λ_{OB}) is unequal to the thermal conductivity of the underburden (λ_{UB}). During this simulation temperature gradient was constant throughout the whole model, even though the thermal conductivity varied between overburden, reservoir and underburden. As a result the model was not in equilibrium before the simulation started.

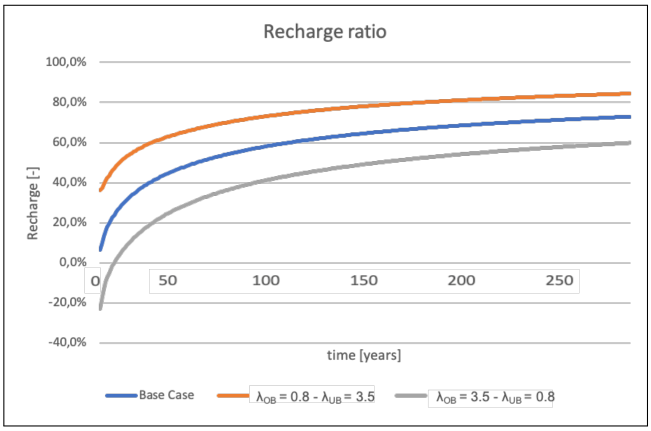

Figure D.1: The results for the recharge ratio with an incorrect initial temperature distribution.

Figure D.1 shows the effect of an incorrect initial temperature distribution. Because the thermal gradient was not adapted to the thermal conductivity of the model, during the first timestep heat starts to flow to achieve a temperature distribution with a constant heat flux. In the case with λ_{OB} = 0.8 and λ_{UB} = 3.5, during the first timestep of the simulation heat flows from the underburden towards the reservoir. The initial temperature gradient in the underburden was too large for the corresponding thermal conductivity, compared to the reservoir and the overburden. The heat that flowed from the underburden towards the reservoir is considered as thermal recharge. Therefore, is the initial recharge ratio, and all the subsequent result for the the case with λ_{OB} = 0.8 and λ_{UB} = 3.5 too large. In the case with λ_{OB} = 3.5 and λ_{UB} = 0.8, during the first timestep of the simulation heat flows from the reservoir towards the overburden. The initial temperature gradient in the underburden was too small for the corresponding thermal conductivity, compared to the reservoir and the overburden. The heat that flowed from the reservoir towards the underburden is considered as negative thermal recharge. Therefore is the initial recharge ratio, and all the subsequent result for the the case with λ_{OB} = 3.5 and λ_{UB} = 0.8 too small.

These results emphasize the importance to chose the correct initial temperature distribution.