Estimation of Sustainable Production Limit by Using Lumped Parameter and USGS Hydrotherm Simulation

YAGIZ BOSTANCI

Thesis of 60 ECTS credits submitted to the School of Science and Engineering at Reykjavík University in partial fulfillment of the requirements for the degree of Master of Science (M.Sc.) in Sustainable Energy Engineering

June 2018

Supervisors:

Einar Jón Ásbjörnsson, Supervisor
Assistant Professor, Reykjavík University, Iceland

Examiner:

María S. Guðjónsdóttir, Examiner
Department Head, Mechanical and electrical engineering. Reykjavik University, Iceland
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May 2018
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Abstract

Sustainable development studies have been frequently discussed in recent decades. Many modeling methods have been developed to maintain the production and investigate the nature of geothermal reservoir. The objective of this thesis can be summarized by defining sustainable production limits by using time and cost-effective models for given geothermal reservoirs. Lumpfit V3 software which based on nonlinear iterative least squares technique and developed by ISOR has been used to simulate reservoir conditions. USGS Hydrotherm simulations were created using Lumpfit V3 results. The purpose of using software of USGS Hydrotherm is to create the reservoir geometry which is ignored in the first step of Lumpfit V3 and to analyze the response of the reservoir according to the parameters applied. These two software packages were used to investigate the sustainable limit of Munadarnes low temperature geothermal reservoir. In this sense, thermal front velocity modelling of the Munadarnes reservoir was investigated in the previous years as a master thesis assuming that 100% of the injected fluid reaches the production well. In this thesis sustainable production limit of Munadarnes low temperature geothermal reservoir have been investigated. Water level changes, production rates and pressure data for the MN-08 well between 2007 and 2017 were provided for this thesis by Reykjavik Energy. All the lumped tank models have been simulated. Best fitting model and properties of reservoir were found in two tank open model. However, fit that obtained 3 tank closed and 3 tank open models were quite similar the fit that obtained from 2 tanks open model. For this reason, 56 different scenarios were simulated to estimate sustainable production limit of Munadarnes reservoir. Based on Lumpfit V3 result estimated the total area that covered by confined reservoir is 16.1 km² with average permeability of 1.6 mDarcy. 2-D reservoir modeling of the Munadernes geothermal resource was carried out using software of USGS Hydrotherm and 4 different production limits were simulated for a total of 32 years - with injection and without injection. Based on ground-water flow and heat transport results simulated by USGS Hydrotherm, there was no significant temperature change observed in production well at the end of the simulation period. Overall results showed that changes in water levels have a significant impact on the determination of the sustainable limit of the Munadarnes low temperature geothermal reservoir.
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date

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Yagiz Bostanci
Master of Science
Dedicated to my parents and all the good people in my life.
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Author
Yagiz Bostanci
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<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>EJ</td>
<td>Exajoule</td>
</tr>
<tr>
<td>TW</td>
<td>Terawatt</td>
</tr>
<tr>
<td>GW</td>
<td>gigawatt</td>
</tr>
<tr>
<td>RMS(m)</td>
<td>Root mean square</td>
</tr>
<tr>
<td>STD(m)</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>DF</td>
<td>Degree of freedom</td>
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# List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value/Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_r$</td>
<td>Reservoir volume</td>
<td>$m^3$</td>
</tr>
<tr>
<td>$\phi_r$</td>
<td>Porosity</td>
<td>-</td>
</tr>
<tr>
<td>$\rho_w$</td>
<td>Density of water</td>
<td>Kg/m$^3$</td>
</tr>
<tr>
<td>$c_t$</td>
<td>Total Compressibility</td>
<td></td>
</tr>
<tr>
<td>$Q$</td>
<td>Constant production</td>
<td>Kgs$^{-1}$m$^2$</td>
</tr>
<tr>
<td>$\sigma_1$</td>
<td>Mass conductance of resistor</td>
<td>Kg/s/Pa</td>
</tr>
<tr>
<td>$k$</td>
<td>Permeability</td>
<td>Darcy</td>
</tr>
<tr>
<td>$K_n$</td>
<td>Storage capacity</td>
<td>Kg/s/Pa</td>
</tr>
<tr>
<td>$A_j$</td>
<td>Storage coefficient</td>
<td>-</td>
</tr>
<tr>
<td>$L_j$</td>
<td>Storage coefficient</td>
<td>-</td>
</tr>
<tr>
<td>$p$</td>
<td>Pressure</td>
<td>Bar</td>
</tr>
<tr>
<td>$B_t$</td>
<td>Storage coefficient</td>
<td>-</td>
</tr>
<tr>
<td>$h_r$</td>
<td>Specific enthalpy of the porous-matrix</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>$C$</td>
<td>Turbulence coefficient</td>
<td>-</td>
</tr>
<tr>
<td>$\nabla$</td>
<td>Spatial gradient</td>
<td>m$^1$</td>
</tr>
<tr>
<td>$k$</td>
<td>Matrix of storage capacity</td>
<td>-</td>
</tr>
<tr>
<td>$S_w$</td>
<td>Saturation of water</td>
<td>-</td>
</tr>
<tr>
<td>$k_{rw}$</td>
<td>Relative permeability</td>
<td>dimensionless</td>
</tr>
<tr>
<td>$\mu_w$</td>
<td>Viscosity</td>
<td>Pa-s</td>
</tr>
<tr>
<td>$g$</td>
<td>Gravity</td>
<td>m/s$^2$</td>
</tr>
<tr>
<td>$\hat{e}_z$</td>
<td>Unit vector in the z-coordinate</td>
<td>dimensionless</td>
</tr>
<tr>
<td>$q_{sf}$</td>
<td>Flow-rate intensity of a fluid-mass source</td>
<td>kg/s-m$^3$</td>
</tr>
<tr>
<td>$K_n$</td>
<td>Thermal conductivity</td>
<td>W/m$^{-1}$K</td>
</tr>
<tr>
<td>$I$</td>
<td>Identity matrix of rank 3</td>
<td>dimensionless</td>
</tr>
<tr>
<td>$dT/dx$</td>
<td>Temperature gradient</td>
<td>K/m</td>
</tr>
<tr>
<td>$c$</td>
<td>Specific heat capacity</td>
<td>$J/(kg\cdot K)$</td>
</tr>
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Chapter 1

Introduction

Geothermal energy utilizes stored thermal energy by using ground water or other working fluids to transport heat from the subsurface to the surface. The increased heat in the lower layers of the crust and the tendency of the upper layers to cool down with the lithosphere causes this mechanism to operate and repeat as infinite loop. The temperature of the crust often increases with respect to depths and this is called geothermal gradient (1-degree Celsius increment per 33 meters) However, some regions of the Earth’s Crust such as Iceland, Japan, Turkey, Philippines, and others as a result of tectonic activity and thermal decay of radioactive isotopes have a high enough geothermal gradient that can be economically and technically exploited.

Stored thermal energy at 3 km depth within the continental crust is estimated to be approximately 43 x 10^6 EJ (EPRI, 1978). This is greater than the world’s primary energy consumption of 606.6 EJ in 2015. Expected increase in the world’s primary energy consumption in 2030 is 699.4 EJ (EIA, 2017). Due to recharge of the resource by upward flows of heat from Earth’s Core to surface, geothermal energy can be classified as a renewable energy source with low levels of greenhouse gases. Geothermal energy represent itself as an environmentally friendly source of energy that can be used for many years but requires accurate modeling. Considering this, geothermal energy has taken its place among the alternative energy forms which can be used to meet the increasing energy needs of human beings.

One of the crucial point with energy cycle is efficiency. The topic of this thesis is the sustainability of geothermal reservoirs. The methods that were used to simulate for the case studies are also time and cost efficiency. This is different from with other models such as detailed numerical models. The objective of this thesis can be summarized as defining sustainable production limits by using time and cost-effective models for given geothermal reservoirs. Detailed information for these models is given under the section 3. All the methods are explained under the methodology section and applied to the Munadarnes geothermal reservoir which located West Iceland. Many modeling methods have been developed to maintain the production of geothermal reservoir. Some of them are simple modelling which geometry of reservoir greatly simplified and lumped parameters modelling which geometry of resource ignored and detailed complex modelling or conventional modelling that required detail information and data of the resource.
In this thesis, a lumped parameter model is used to define sustainable production limit of geothermal reservoir and flow and transport equations in order to define the response of the reservoir to estimate the behavior of geothermal reservoir under given parameters. Lumpfit software which was developed by Iceland GeoSurvey (ÍSOR) and USGS Hydrotherm software which developed USGS (United States Geological Survey) have been used to run simulations and build a sustainable model for Munadarnes low temperature geothermal reservoir.

Models that mentioned above are a type of dynamical modeling. The theoretical idea of using dynamical modelling can be explained as building a model that uses future forecasts by using data that was recorded during the utilization stage of resource and estimating the response of geothermal reservoir. By taking advantage of data that recorded or monitored utilization stage of reservoir will give idea about future forecast of area and possible locations of wells. Modeling such a system is used to find a mathematical finding that matches the calculated response as closely as possible to the observed response (Li, 2016). The sustainable use of geothermal energy is the main topic of this thesis, as well as the methods and applications that can be applied to achieve sustainable production.

This study can be summarized by 2 questions ‘What is the sustainable model of geothermal utilization and what methods should be applied to achieve it? As has already mentioned above, by taking advantage of lumped parameter models and USGS Hydrotherm sustainability of geothermal reservoir is we can arrive at this end-point. Section 2 includes theoretical information about sustainable management. These are; classification and renewability of geothermal reservoirs, nature and production capacity and sustainability goals and gains. Section 2 starts with a basic definition about geothermal terminology, classification of geothermal systems based on temperature, enthalpy and physical state, and continues with the production models that is proposed the by Icelandic working group. The chapter ends with sustainability goals and gains. Section 3 presents lumped parameter model that located dynamic modelling approaches and ignored geometry of source. Lumpfit V3 software which based on nonlinear iterative least squares technique has been used to simulate reservoir conditions. USGS Hydrotherm simulations were created using Lumpfit V3 results. The purpose of using software of USGS Hydrotherm is to create the reservoir geometry which ignores the first step of lumped parameter modelling and to analyze the response of the reservoir according to the parameters to be applied. USGS Hydrotherm simulates ground water flow which based on Darcy’s law for flow in porous media and thermal energy transport equations. Section 4 presents case studies: Methods that presented Section 3 are applied Munadarnes low temperature geothermal systems in West Iceland. Change in water level and production history of geothermal areas are used to compute sustainable production limit for case studies. Then response of the reservoirs were examined by software of USGS Hydrotherm.
Chapter 2

Sustainable Utilization

Sustainable development studies have been frequently addressed in recent decades. The Brundtland report has been pioneer in the popularization of the area of sustainable development. According to Brundtland report in 1987 definition of sustainable development is:

‘Development that meets the needs of the present without compromising the ability of future generations to meet their own needs’ (World Commission on Environment and Development, 1987).

This definition is more general explanation of sustainable development and reflects the main point of sustainability in which needs can be met or improved upon for all human needs without harming the ability of future generations to have the same opportunities. In this section, the term of sustainability and renewability discussed for geothermal energy. Additionally, we also address major issues such as how to reach sustainable management, goals and indicators of sustainable management and their application for geothermal energy, with reference to the work of authors who have worked on this subject.

Sustainable management can be defined as bringing the currently used resource to a fixed and sustainable point and efficiently using the same source for a long time. In the light of these information’s we can assume that sustainability depends on the utilization mode of source. Sustainability and renewability of geothermal energy has been discussed and published in the past few decades, and papers by Wright (1999), Stefánsson (2000), Rybach et al. (2000), Cataldi (2001), Sanyal (2005), Stefánsson and Axelsson (2005), Ungemach et al. (2005), and O’Sullivan and Mannington (2005) provide a detailed explanation of the issue. In this thesis study, sustainability studies have been carried out by simulating the data of the Munadarnes reservoir used for district heating by using the knowledge of working authors in this subject. Under this heading, the author provided few subheadings to achieve sustainability goals and gains.

Sustainable development additionally includes meeting the energy needs of mankind and geothermal resources can certainly play a role in sustainable energy development since it is has been widely suggested that they should be classified among the renewable energy sources (Axelsson G., 2012). Differences between renewability and sustainability of sources basically explain as a rate that renovation of source. But, this will cause another question, the question of the renewal period. All the questions that related classification of geothermal energy are discussed in the following sections. As already mentioned in introduction Earth’s geothermal energy potential (down to 3 km within continental crust) is greater than existing human electricity consumption and future needs. Valgardur Stefánsson’s results on the worldwide technical potential of geothermal sources for electricity is 240 GWₑ (Stefansson, 1998) However, theoretically case which based on Iceland and USA reflect that electricity potential of sources to be 5-10 times (hidden resources included) greater than estimated resources.
Furthermore, value range of estimated electricity will be between $1 - 2 \text{ TW}_e$ taking into account the rest of the world (Stefansson, 2005). However, the Earth's ultimate geothermal potential was not accurately predicted in the course of available knowledge and technology. Although the use of geothermal energy has grown rapidly in recent years and it is expected to continue to grow, the potential of the Earth is still very great compared to available potential. Energy production capacity of geothermal systems is highly variable, and as well as it’s controlled pressure decline in the reservoir. Due to the production stage, mass extraction can cause a pressure decline and it suggested that this decline will continue with the time. Types of reservoir (closed or open systems) additionally can affect behavior of the reservoir pressure. Production potential is suggested to be controlled by lack of water instead of lack of thermal energy (Axelsson G., 2012) (Axelsson & Stefánsson, 2003). Types of geothermal reservoir and their properties is discussed under the section 2.2. Long-term usable energy resources can be obtained and served to the human being through accurate and sustainable use of power that controlled by earth crust. This energy, which can be controlled in small quantities at the below the earth's crust, is not only using for generating electricity but also can be used to district heating and many applications.

Future estimates can be made by looking at the past performance of the resource and compared with the direction of the data obtained by reservoir evaluation methods. The production levels to be achieved in the same time may reflect the sustainable limit of the reservoir. Resource assessment methods can be classified with detailed numerical models, lumped parameter models, simple models and volumetric models. The sustainability can be assigned by resource assessment methods to maximize the gains from the source and ensure the longest and most efficient use of the source with a fixed and sustainable production limit. By taking advantage of sustainable production limit, investments that are planned of geothermal area such as number of production, reinjection and observation wells, additional pipe and turbine systems are proposed to be developed stage by stage. This type of research is expected to result in more stable investment and increase the number of investors who willing to invest in geothermal energy.

2.1 Classification and renewability of geothermal reservoirs

In this section classification of geothermal resources is defined and takes into account the results of classification renewability of resources. As already mentioned at previously sections, geothermal energy can be found in active areas of volcanism related to plate tectonic activity. However, despite the greatest concentration of geothermal energy being found in areas with plate boundaries and related volcanic activity the resource can also be found in sedimentary systems as warm ground water. As can be expected, nature and classification of geothermal energy represents amount of energy that stored in crust. There is a large amount of variation in access the geothermal reservoirs due to the distribution of area that has geothermal potential. Some cases geothermal energy is found in populated, or easily accessible areas which reveals other problems that need to be addressed such as a geothermal field that is located near a town or farming areas. In addition, that, geothermal energy can be found in areas at depths too deep to justify extraction or with limited accessibility such as the ocean floor, mountains regions and under glaciers and ice caps. Before the classification of the geothermal resources we need to discuss a few terms. These are; geothermal field, geothermal system and geothermal reservoir.
Geothermal systems and reservoirs are classified across many different aspects, such as temperature of reservoir or enthalpy, physical state (liquid dominated, steam dominated or mixed) their nature and geological setting. Table 2-1 represents classification of resource based on temperature, enthalpy and physical state.

Table 2-1: Classifications of geothermal systems based on temperature, enthalpy and physical state taken from (Bodvarsson, 1964; Axelsson and Gunnlaugsson, 2000).

<table>
<thead>
<tr>
<th>Low temperature systems</th>
<th>Low enthalpy systems</th>
<th>Liquid dominated</th>
</tr>
</thead>
<tbody>
<tr>
<td>With reservoir temperature at 1 km depth below 150°C. Often characterized by hot or boiling springs.</td>
<td>With reservoir fluid enthalpy less than 800 kJ/kg, corresponding to temperatures less than about 190°C.</td>
<td>Reservoirs with water temperature at, or below the boiling point.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Medium temperature systems</th>
<th>High enthalpy system</th>
<th>Two-phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>High temperature system</td>
<td>With reservoir fluid enthalpy greater than 800 kJ/kg</td>
<td>Reservoirs where steam and water co-exist, and pressure and temperature follow the boiling curve.</td>
</tr>
</tbody>
</table>

Vapor-dominated Reservoir temperature is at, or above, the boiling point at the prevailing pressure in the reservoir.

Based on (Axelsson, 2008) geothermal systems are defined as 6 different way by their geological settings and nature these are;

a. *Volcanic systems* are directly or indirectly connected to volcanic activity. Heat sources of such systems are magma or hot intrusions and mostly located inside or near the volcanic forms. Water flow of the system mostly controlled by permeable fractures and fault lines.

b. *Convective systems* can be called heat mining from the rocks. The areas where located mostly deeper than 1 km and due to tectonic activity can be hosted heat source as a hot crust. These formations have a heat flow which greater than average. Geothermal water has circulated and recharged by vertical fractures and their permeability.

c. *Sedimentary systems* are found in the world's major sedimentary basins. These systems owe their existence to the occurrence of permeable sedimentary layers at great depths (because of sedimentation progress) and above average geothermal gradients. Sedimentary systems have both conductive and conductive nature, but conductive nature is common heat transfer for the sedimentary systems. Fractures and faults can be affected nature of the system.

d. *Geo-pressured systems* are analogous to geo-pressured oil and gas reservoirs where fluid caught in stratigraphic traps may have pressures close to lithostatic values. Depth of the geo-pressured systems greater than others

e. *Hot dry rock (HDR) or enhanced (engineered) geothermal systems (EGS)* consist of a volume of rock that have been heated by volcanism which called conduction, but
due to lack of permeability of fracture, system cannot exploit as a conventional way. However, experiments have been carried out in various locations to create hydrodynamic fractures in order to create artificial reservoirs in such systems or to strengthen existing nets.

f. Shallow resources located near the surface of the Earth’s crust that has thermal energy. By taking advantage of heat pumps, the use of shallow resources is steadily increasing (Axelsson G., 2008).

On the other hand, it is rather difficult to mention geothermal energy as renewable except in some systems and natures and this can be challenging to define. Energy transportation of a geothermal system can be taken as a fundamental point for talk about renewability, and main point that behind the renewability is; time scale differences between replacement of energy and extraction of energy. The recovery of the losses caused by energy extraction within a short period of time indicates that the geothermal reservoir is renewable. If energy transport provided by thermal conduction is possible, we can classify the resource as a ‘renewable’ energy source. If energy transport is not only through conduction, because of a time constant for energy replacement, the recharge period can be much longer than time period for exploitation. All conventional utilization of geothermal energy is based on energy extraction from natural geothermal systems where water transports the energy within the system and water also transports the energy to the surface where the utilization takes place. It is accepted by most authors that production can cause a pressure decline and this can result in an increased requirement for the recharge of water and energy to the system. These conditions are typical for renewable energy sources where replacement of energy takes place on a similar time scale as the extraction.

In some cases, there may be an exception to this rule. These are hot dry rock and the extraction of connate water from some deep sediment. Utilization of hot dry rock requires creating an engineered geothermal system in impermeable rocks by injecting water into one well and extracting heat that stored in the systems by using another well. Because of impermeable nature of these resources, the recharge rate of reservoirs require the same processes as conventional hydrothermal resources such as thermal conduction and the time required to recharge the energy of the reservoir. At this point another question appears which is related to the classification of renewability. Similar conditions can be take a progress in sedimentary systems without natural charge. Also for this reason, the equivocality is the nature of systems and utilization. The effects of the utilization process can also change the nature of system and this is expected to result in a low rate or non-renewable geothermal reservoirs (Stefansson & Axelsson, 2005). As can be seen here renewability of the systems is strictly related to their recharge rate and factors that affecting permeability of a geothermal reservoir. It can be summarized that a common agreement among researchers is that geothermal energy ‘should be classified as a renewable energy source’.

2.2 Nature and production capacity

As was already mentioned before, geothermal resources predominantly are classified as renewable because of their recycled energy current. This definition is supported by another definition, many authors whose working on geothermal energy has touched on this topic. For instance, according to Stefansson: the energy sources that are called renewable must recharge/replace in a natural way with an extra amount of energy replacement and time
period of recharge corresponding to time scale of extraction period (Stefansson, 2005). On the other hand, (Axelsson G., 2008): classification of resources can be an oversimplification because of a potential double nature of the resource - a combination of energy current and stored energy (Axelsson, Stefansson, & Björnsson, 2005). It is difficult to estimate the renewal rate of these two components but the idea that all authors and (Stefansson, 2005) are agree upon is that the ‘renovation of stored energy takes a place slowly’.

Although geothermal resources are agreed to be renewable, there are limits for production. Utilization includes mass and heat extraction from reservoir by using boreholes and this process can be named as a transportation of mass and heat. Also, this two-component process can create an undisturbed natural state of a geothermal system controlled by global pressure changes in system. Production stage is going to affect the natural systems because the flow of heat and mass which is forced to act by external intervention will temporarily affect the pressure values of the reservoir. This process follows pressure drop due to production. For this reason, ‘reservoir pressure’ is crucial component that relate to the utilization of geothermal resources. One of the most important component of the geothermal system is energy content also called enthalpy. Enthalpy depends on the phase of reservoir for instance: in single phase related only temperature and pressure and these two-value defines physical state of the reservoir. Two phase fluids are not only related pressure and temperature but also connected additional parameters that water saturation, enthalpy chemistry of water and geological settings of reservoir (Axelsson G., 2008). The capacity is also controlled by the energy content which is determined by the temperature and the reservoir size and this is the main factor that effects the temperature drop. Proper re-injection management is usually required to maximize / maintain production capacity.

The big picture of the system can be called cycle of the pressure decline. Because of the pump depth, there is a technical limit to pressure decline in a well. Another component to determine the available energy content is temperature or enthalpy of the extracted mass. As mentioned before all of components take place in a cycle. Furthermore, few components can be added this cycle to better understand big circle these are:

- The size of the geothermal reservoir.
- Permeability of the reservoir rocks and reservoir storage capacity (Geological settings).
- Water recharge.
- Geological structures.

Pressure decline in geothermal system reason of mass extraction will be lead to major and minor change in whole system these are (Axelsson G., 2016):

- Discharge from steam-vents often tend to increase
- Increased recharge from outside and cooling of reservoir
- Cooling of reservoir result of boiling affect
- Surface subsidence and mixing water
- Chemical changes due to recharge and/or boiling
- Change in micro-seismic activity
The pressure drops and their effects on the geothermal reservoir may give some knowledge of the geothermal system, as well as its nature and characteristics. Also, knowledge from past studies can be a way to obtain sustainable utilization information for given geothermal reservoir. Strategy of data collection can be explained as initial data from surface explorations, if available, and additional information from reconnaissance drilling such as well logging and well testing. Some of this data can provide monitoring and crucial information for system. (Axelsson G., 2008) geothermal resource can be classified ‘as either open and closed with strictly related long-term behavior and boundary conditions’. Figure 2-1 is a graphical representation of the system depending on pressure and time.

Figure 2-1: Schematic comparison of pressure decline in open (with recharge) or closed (with limited or no recharge) geothermal systems at a constant rate of production taken from (Axelsson G., 2008).

In order to fully exploit the potential of geothermal source, a series of production method strategies discussed by authors who are working in this article have been proposed. Simulating production methods can be based on achieving a sustainable limit and maintaining the reservoir at this limit, increasing the useful life and ensuring continuity in production with constant flow. All these ideas and models have led to the question of whether geothermal energy could be produced at a sustainable level. In this chapter some of these discussions have been addressed and in addition production models and sustainable approaches have been examined. In addition, definition of sustainable production was already mentioned Icelandic working group (G. Axelsson, H. Ármansson, S. Björnsson, Ō. G. Flóvenz, Á. Gudmundsson, G. Pálmason, V. Stefánsson, B. Steingrímsson and H. Tulinius.) and according to them, the definition of sustainability can be summarized as "the sustainable production of geothermal energy from a single geothermal system". Also, this definition does not provide for few variables that cannot remain constant such as, technological advances, environmental and financial aspects, all of which can be expected to change with the time life of system. Whole and detailed explanation for sustainable production limit which is represented by E₀ given below according to Icelandic work group (Axelsson, et all., 2001):
For each geothermal system, and for each mode of production, there exists a certain level of maximum energy production, \( E_0 \), below which it will be possible to maintain constant energy production from the system for a very long time (100-300 years). If the production rate is greater than \( E_0 \) it cannot be maintained for this length of time. Geothermal energy production below, or equal to \( E_0 \), is termed sustainable production while production greater than \( E_0 \) is termed excessive production (Axelsson, et al., 2001).

The definition that mentioned above represents the total removable energy and as can be expected strongly related with nature for given system. The Nature of system can be described as; natural discharge, injection and mode of production. It should be mentioned that, in practice sustainable production limit \( (E_0) \) is not predictable especially, beginning of the utilization but can be estimated by available data that recorded (Axelsson & Stefánsson, 2003; Axelsson G. , 2012). According to Axelsson there are two fundamental issues when sustainability of geothermal system has been analyzing and evaluated. These are use of a reservoir with a sustainable behavior in some way and time period of this progress. Also, geothermal resources can be utilized for several decades without significant decline and it shows that the reservoir will reach a new semi-equilibrium in physical conditions during long-term energy extraction. In economic way of assessing a geothermal project is mostly on time-scales of 25-30 years (Axelsson G. , 2008; Axelsson G. , 2012). When compared to the formation process of system which is more than millenniums. Natural flow manner serves as an explanation of this time scale. But the Icelandic working group proposed time scales of the order of 100-300 years (Axelsson, et al., 2001). Figure 2-2 represents the essence of the definition of sustainable production is to capture for the time scale proposed by the group. For instance, if the production is below the \( E_0 \) it should be continued to increase production limit. This is because when this is encountered the opposite reaction should be taken, which means production above the limit, in this case production must be reduced before the period that decided before, if it is desired to catch the sustainable limit and maximize the reservoir.

![Figure 2-2](image-url)

**Figure 2-2:** A schematic graph showing the essence of the definition of sustainable production. \( E_0 \) represents sustainable production limit for given reservoir. If the production limit more than sustainable level production of the reservoir called excessive. Taken from (Axelsson & Stefánsson, 2003).
Due to a lack information during the exploration and utilization steps, the estimation of sustainable production level $E_0$ will be difficult. In some cases, considerable knowledge and experience are obtained, it can be difficult to estimate production capacity and therefore the level of sustainable production. Also it should be mentioned that; it can be expected that the level of sustainable of a given geothermal resource will increase with time which is depending on the knowledge of the system (Axelsson G., 2008). Thanks to rapid advances in technology this will increase utilization efficiency and time scale that mention above. With this, focusing on only one production in geothermal production may result in a mistake. This is because utilization system and area that related geothermal energy is not only controlled single power company but also few companies can be used thermal energy at the same field. Moreover, rate of production values will change company to company which means production rate may be greater than $E_0$ while others below the limit. In this cases time period to get new equilibrium and value of equilibrium will be affected. This leads us to possible modes of production for the individual geothermal systems that can be included in the more general sustainable geothermal utilization diagram shown in Figure 2-3.

**Figure 2-3:** Different production modes for geothermal systems which can be incorporated into sustainable geothermal utilization scheme. Number one represents sustainable production which is not realistic, second line represents step-wise development, while third line over production and forth line represents over production for 30-40 years. Taken from (Axelsson, 2010).

Standardized methods for modelling are as follows:

1. Continuous production for 200 years (excluding variations due to temporary demand such as annual changes). This is not a realistic option since the sustainable production capacity of geothermal systems is not known beforehand. For this reason, a kind of testing period is required until the initial sustainable potential is evaluated.

2. Production has increased in several steps until sustainable potential has been assessed and sustainable reach has been reached.

3. Over production (unsustainable) for a few decades (maybe about 30 years), with a total break between them, somewhat longer than the production times (about 50 years), where a geothermal system can be recovered almost completely.

4. Over-production for 30-50 years, followed by a constant, but much less, production for 150-170 years. Subsequent production will therefore be far less than the
sustainable potential in continuous production (Ketilsson, et al., 2010).

The second mode of production modelling can be called stepwise development which means production rate will increase respect to period of developing stage. During this period, by using historical data that was recorded before or after the first stage of development gives the opportunity to estimate production rate that to be used next step. By taking advantage of this, not only is sustainable production limit determined, but also it may be possible to determine the financial requirements that are needed to construct the further steps. In this way, favorable conditions for timing of the income are provided for the timing of the investment, and lower long-term production costs have emerged than what can be achieved by developing the field in one step. Combining the step-wise development approach with the concept of sustainable development of geothermal resources gives a chance to estimate an attractive and economical way to use geothermal energy resources. Considerable time scales are needed to understand the boundary conditions of geothermal system during the utilization process. As expected, there is a direct proportion between the parameters for development and duration of observation. It should be limited at some point because due to production stage in some cases as the water level of reservoir may drop and it may result in an increase of the energy recharge to system. In most cases monitoring should be continued 5-10 years to determine parameters. In the light of this information, step-wise development mode reflect nature of geothermal energy (Stefansson & Axelsson, 2005). Figure 2-4 represents the conventional stepwise development method with production rate vs time.

![Figure 2-4: Typical Stepwise Development of a Geothermal Resource.](image)

When referring to stepwise production, a point must be emphasized that overinvestment in the field is avoided. On the other hand, will take a long time to reach goals such as income and maximum production rate. Taken from (Stefansson & Axelsson, 2005).

In the beginning of the developing stage some cases such as Turkey, rapid initial development can be logical due to gain on sale of unit which is 105 $/MW (Republic of Turkey Ministry of Economy, 2015). But it should not be forgotten that some of equipment
will become useless due to exploitation of reservoir. Because of overexploitation, production rate may decrease and the time scale that is needed to be recovery of reservoir will be increase (Axelsson & Stefánsson, 2003; Stefansson & Axelsson, 2005; Axelsson G., 2012).

2.3 Sustainability goals and gains

Efforts to better understand the nature and formation mechanism of geothermal energy and to control this power in nature are still going on. In addition, the sustainability of geothermal energy has begun to be considered by the countries and policy making with legislation and regulatory frameworks. Countries such as Turkey which import energy to supply their energy needs should set sustainability goals. By taking advantage of incentives given by governments, investors will tend to invest sustainable energy. According to (Axelsson, 2012) developing a sustainability policy involves the following two steps:

(A) Identification of overall sustainability targets, including basic sustainability objectives, aimed at whether they are resource, economic, environmental or social.

(B) Define specific Sustainability gains based on goals. Also, gains that result of goals should be linked and evaluated sustainability of system. Most of authors whose working on it come up with same idea about number of indicators and their degree of complexity (Axelsson G., 2012).

The targets for geothermal development can vary from country to country, but from a technical point of view it will be understood to be based on the same foundations. To prove this, policy goals for geothermal development of Turkey’s and Iceland’s have been summarized below. Eleven proposed general targets for geothermal development in Iceland are covered by a working group in Iceland, summarized below (Axelsson G., 2012; Ketilsson, et al., 2010; Shortall, 2010).

- Resource management/renewability (2 goals)
- Efficiency
- Research and innovation
- Environmental impacts
- Social aspects
- Energy security, accessibility, availability and diversity (2 goals)
- Economic and financial viability (2 goals)
- Knowledge sharing

In the energy policy of Turkey in recent years, domestic, increasing the renewable and environmentally friendly use of energy resources and important encouragements on the assessment of these sources in electricity production are conducted. These goals summarized below (Yılmaz, 2015).

- Increase the use of renewable resources to generate electricity
- Promoting renewable energy production in a safe, economical and cost-effective manner
- Reduce greenhouse gas emissions
- Develop relevant mechanical and / or electro-mechanical manufacturing industry
- 600 MW geothermal potential to take over (821 MW reached in 2017 (TÜİK, TEİAŞ, & EPDK, 2017))
As a result of measures to be taken for the use of domestic and renewable energy sources, the share of natural gas in electricity generation is guaranteed to be lower than 30%.

In addition, the general principle is that the Ministry of Economy will only provide support during the investment period (General Incentive System) for all kinds of electricity generation investments and support through purchase guarantees and tariffs during the operating period. In this framework; Hydropower, wind, geothermal, solar and biomass investments are supported under the general incentive System. Proposed supports summarized like; VAT exemption, customs tax exemption, revenue tax withholding support.
Chapter 3

Methodology

The importance of achieving sustainable use of the reservoir has been discussed previously in this thesis. This chapter contains information about the estimation of the sustainable production limit for a geothermal reservoir and useful methods to find sustainable production modelling. The chapter also includes detailed information about lumped parameter modelling and the Lumpfit V3 software which is used for simulation of the changes in the reservoir water levels vs pressure and USGS Hydrotherm that is a simulation tool of two-phase ground water flow and heat transport in the temperature range of 0 to 1200 degrees Celsius.

Many methods and approaches have been used to assess geothermal resources during the utilization stage. The main purposes of those methods are estimations of the resource temperature, predicting the production response and estimating production potential of resource. Requirement of the successful utilization/development is to simulate as accurate as possible a given resource. Here is the list of main methods that used for assessing:

1. Deep temperature estimates (based on chemical content of surface manifestations).
2. Surface thermal flux.
3. Volumetric methods (adapted from mineral exploration and oil industry).
4. Decline curve analysis (adapted from oil/gas industry).
5. Simple mathematical modelling (often analytical).
7. Detailed numerical modelling of natural state and/or exploitation state (often called distributed parameter models). (Axelsson G. , 2008)

More generally it can be classified as a volumetric assessment method or dynamic modelling method. The mechanism of the volumetric methods are estimating total heat that stored in volume of rock, both thermal energy that located rock matrix and water / steam in the pores. Volumetric methods are mostly used in first phase of assessment, if a classification according to the usage order is needed. A few parameters such as surface area and thickness of resource estimates by using geological and geophysical data that given area. As a result, possible temperature conditions are assumed. Also, total energy content of systems is estimated by using estimates of reservoir porosity and thermal properties of rock involved. The most important factor with the volumetric method is recovery factor ($R$) and can be represented as the energy that may be technically recovered (Axelsson G. , 2008). Dynamic modelling can be separated into three subsections which are simple analytical, lumped parameter and detailed numerical models. The goal of a simple analytical and complex...
modeling is to predict the future by using the data collected before and during the development stage when a sustainable resource is obtained. Another issue is the time scale that is required to consume, simulate and/or build a model. As can be expected, time that need to build and/or simulate simple analytical model is shorter than complex numerical models.

### 3.1 Lumped parameter modelling

Several lumped parameter models have been published by authors who are working in the field of reservoir engineering. Some of the authors working on geothermal fields which contain dissolved solids and gasses as well as water, has been upgraded lumped modelling based on the general material-energy balance equation given by Whiting and Ramey (1969). Lumped parameter modeling, which involves dynamic modeling approach due to successfully studies that done by authors, has been proved itself as a reasonable consuming of time and fund alternative (Axelsson G., 1989; Alkan & Satman, 1990; Axelsson, Björnsson, & Quijano, 2005).

In the lumped parameter models included in the dynamic modeling approaches, the reservoir geometry is theoretically ignored and properties integrated into lumped values (Axelsson G., 2017). In other words, lumped parameter modelling is the representation of physical state in given source by using mathematical equations that based on fluid flow, heat transfer and pressure changes. Equations that published by authors whose working on this field are purposed same aim. These mathematical approaches can be explained as a respond to the reservoir along the production phase and can also be used to predict future estimates. At the same time, these approaches and calculations are included in the literature on reservoir engineering. In the light of this information, data that uses simulation of reservoir i.e. change in water level and temperature during the utilization stage, can be monitored and obtained. Also, it should be mentioned that the data recorded and obtained in the process can be used to correct the simulation. This can be then used to define difference between calculated and observed data. The last step to conclude all these steps is called history matching or data fitting stage. The following paragraph contains different approaches on lumped parameter modelling. Representation of lumped parameter modelling is based on (Axelsson, 1989) where Axelsson describes an efficient method that uses inverse equations to derive a lumped parameter model and obtain pressure change in system which can use to simulate respect to quality of data. To estimate the model parameters, the nonlinear iterative least squares technique is used to automatically observe the analytical response functions of the collected models (Axelsson, Björnsson, & Quijano, 2005). In the same study it can be seen that an easily lumped network consists of 3 main parts. These are the central tank which connected by resistance with the other/outer part of reservoir and outer and deeper parts of reservoir.

But based on (Sarak et al., 2005) there is a missing point at (Axelsson, 1989) which is related to fluid flow within the reservoir and neglects spatial variations in thermodynamic conditions and reservoir properties. This represents the reservoir that has an average enthalpy and non-condensable gas content of fluid which cannot match and is not possible to simulate phase and thermal fronts and can’t help to define different wells spacings (Sarak, Onur, & Satman, 2005). Also, one more difference mentioned in the same paper is the ‘outer parts of the reservoir’. Definition of a simple lumped parameter model is agreed to be tank or capacitor network. As mentioned above the geothermal reservoir is separated into three different parts. All complex lumped parameter models are derived from this simplified lumped parameter model and are adapted to different reservoir conditions. Due to different behaviors of the reservoir conditions according to the geological area where the geothermal field is located has required updating the modeling methods. Figure 3-1 represents different parts of a geothermal reservoir.
Figure 3-1: Parts of a geothermal system. Central part of reservoir represents production and reinjection area of the source. Circle which has an arrow represent injection wells and without arrow means production wells. There is another recharge source which works with injection wells and showed around big circle that include central part. Taken from (Sarak, Onur, & Satman, 2005).

In some cases, the number of parts can be changed from reservoir to reservoir i.e. deeper, hidden and outer. In addition to that, distribution of those parts/tanks can be variable, but in all cases overall system is connected each other. In areas where recharging is in place, is also located same region. But at this point we can separate the part of the recharge reservoir that provides heat transfer and the part to which the water is recharged. The central part of reservoir will not change the conditions of the heat source in this part which is the heat source of the reservoir. The pressure and temperature can remain constant in the heat source as long as there is no tectonic and volcanic activity to change the structure of the heat source. This area is represented as a recharge tank that supplies recharge to geothermal system in lumped parameter model. It would be beneficial to show the reservoir areas in tank form to better understand the system. In this way the relation of the reservoir parts to each other will be better understood. As mentioned earlier, the system is divided into 3 different sub-regions. These sub-regions and their connection shown in Figure 3-2. The production area is located within the boundaries of the central reservoir and connected with outer parts with flow resistor. Same connection located outer and deeper part of reservoir as well. Tanks that draw in figure simulates storage capacity system and their parts. Water level or pressure in the tanks reflects same variables in other parts of the tanks. Resistor simulates permeability of layers between tanks.
Each tank in lumped network has a storage coefficient which is $\kappa$ and has a reverse proportion between pressure increase in system, if the load of liquid mass ‘$m$’ is constant. Also, pressure increase of the system can be calculated load of liquid mass divided storage coefficient.

Pressure increase of the system can be calculated as the load of liquid mass divided storage coefficient $p = m/k$. The mass conductance of a resistor which located lumped network representing with $\sigma$ uses to define units of liquid mass per unit time. When mass conductance of a resistor multiplied by impressed pressure differential represent units of liquid mass $q = \sigma \Delta p$. Production from the reservoir is simulated by extracted water that located in one of the tanks and pressure/water level simulates different parts of the reservoir. This is because production area is located in only one tank but water that located system distributed whole reservoir. As can be seen Figure 3-2 first tank which is called the central part of reservoir simulating production part of reservoir and other tanks are the outer part of reservoir. Third tanks which are called the other and deeper part of reservoir connected by a resistor with constant pressure source to recharge geothermal system. Therefore Figure 3-2 is called open system. In opposite situation like without constant pressure connection model would be closed. Tanks that are connected with a constant pressure in lumped open tank models predict more optimistic estimates than closed tank model we can see positive influence the system connected with constant pressure, that is going to help to recovery of the reservoir therefore, open systems in lumped parameter model will be more optimistic than the closed systems (Axelsson, Björnsson, & Quijano, 2005; Axelsson G., 2017). On the other words when the system is behaving like a closed model lack of or without recharge and during the long utilization process decline of the water level will cause pessimistic prediction.

Mathematical representation of lumped parameter modelling can be divided into 3 parts, general mass balance equations, mass balance equations in tank system and energy balance equations. On the other words mass balance equations in a tank network system imagined as a matrix system. Energy balance issue of geothermal energy can be solve using isothermal conditions (Axelsson G., 1989; Sarak, Onur, & Satman, 2005; Grant & Bixley, 2011). Also, mathematical representation is reflected input activity model and respond of geothermal system. When the drawdown of reservoir is observed due to lowered pressure or water level recharge water enter the system and tend to keep stable the reservoir pressure in a result of produced fluids. The term of mass influx should be added to mass balance equations (Sarak, Onur, & Satman, 2005). In the light of this information mass balance equation shown in Equation 3.1

$$W_c = W_i - W_p + W_o + W_{inj}$$

(3.1)
Where current mass $W_c$ is equal to the initial mass in reservoir $W_i$, minus what has been produced $W_p$, plus any water influx $W_o$, and re-injected mass $W_{inj}$. Because of compressed water in reservoir during the production stage reservoir pressure going the decrease and causes the compressible water to expand. When the current mass equations upgraded with a reservoir volume of $V_r$ the liquid mass in place is given by Equation 3.2.

$$W_c = V_r \phi_r \rho_w$$  \hspace{1cm} (3.2)

Where $\phi_r$ is reservoir porosity, $\rho_w$ is liquid density. When Equation 3.1 and 3.2 differentiated with respect to time and combined with isothermal compressibility is used, following Equation 3.3 will be obtained for mass flow rates:

$$w_0 - w_p + w_{inj} = V_r \phi_r \rho_w c_t \frac{d_p}{d_t}$$  \hspace{1cm} (3.3)

Where $c_t$ is the total compressibility also, can be defined sum of fluid and formation for reservoir system ($c_t = c_f + c_r$) furthermore compressibility of fluid is defined Equation 3.4 also, formation compressibility is defined in Equation 3.5. Additionally, if we assume that $c_f$ and $c_r$ remain constant which results in a valid assumption of slightly compressible fluid and rock. Net production term may be used instead of production and reinjection (Sarak, Onur, & Satman, 2005). Therefore Equation 3.2 can be upgraded, and new equation showed in Equation 3.6.

$$c_f = \frac{1}{\rho_w} \left( \frac{d \rho_w}{d_p} \right) t$$  \hspace{1cm} (3.4)

$$c_r = \frac{1}{\phi_r} \left( \frac{d \phi_r}{d_p} \right) t$$  \hspace{1cm} (3.5)

$$\omega_0 - \omega_{p,net} = V_r \phi_r \rho_w c_t \frac{d_p}{d_t}$$  \hspace{1cm} (3.6)

Recharge of cold water will effect changes in temperature and density and compressibility in reservoir. Also, it may create non-isothermal effects as well. In such a case a ratio of injection-production with a high error in system will be expected (Sarak, Onur, & Satman, 2005). The basic equations for the simple lumped model are given in the section 3.1 by comparing equations of authors that studied in this area. In this thesis, the new version of Lumpfit software which called LUMPFIT V3 is used to simulate lumped parameter. Lumpfit software is upgraded version of PyLumpfit that created by ÍSOR (Iceland Geosurvey) using equations which were published by Gudni Axelsson, 85, 89. Following section includes detail equations and user interface of Lumpfit software.

### 3.1.1 Lumped software and equations

As already mentioned in section 3 lumped parameter models included in the dynamic modeling approaches methods by using pressure and water level change in reservoirs. Also,
it supports this approach in terms of cost and time consuming. By using hydrological properties of a reservoir, or major parts of reservoir that are lumped together in one or two quantities for each part. This analogous method used in electrical engineering. Also, simple lumped parameter model can be used to predict response of a reservoir to different future production schemes. For these reasons, lumped parameter modelling can be defined as the most powerful modelling.

The theoretical background and methodology for Lumpfit is presented by (Axelsson G., 1985; Axelsson G., 1989) and already mentioned in section 3.1. Data that recorded during the production stage from a reservoir and resulting pressure changes and at the same time one or more of the requirements for the use of the lumped parameter model must be applied these are:

- Data on the nature of a reservoir are limited and detailed numerical modelling is therefore not appropriate or justified.
- The time available for a particular modelling study is limited or a simple method is required as the first stage in the modelling study.
- Funds available for modelling are minimal.
- An independent check on the results of more complex modelling techniques is required (Axelsson G., 1989; Axelsson G., 1985).

Lumpfit tackles the modelling problem as an inverse problem and automatically fits the analytical response functions of the lumped models to observed data by using nonlinear iterative least-squares method for estimating the reservoir parameters. Also, there are 3 requirements that users must be met:

- A time series of the data to be simulated (production and pressure or water level changes).
- Information on units and the data set in general
- Types of lumped parameter tank models to be used

Types of lumped models are one-tank, two-tank and three-tank and all these models can either be open or closed. Differences between open closed models is pressure values. For instance, open tank models connected by a resistor to imaginary reservoir which resulting constant pressure, but closed models are isolated from external reservoirs. As can be expected, one-tank closed model being the simplest. In addition that, practically reservoirs can be represented by open or closed lumped parameter models with one tank and-or few tanks. Following Figure 3-3 represents one-tank open lumped model. Where $\kappa$ is the coefficient of tank mass storage and $\sigma$ is the mass conductance of a resistor. Due to constant pressure network is open system.

![Figure 3-3: One-tank open lumped model taken from (Axelsson G., 1989).](image)
To define the pressure response \( p \) of the open one-tank model to a constant production \( Q \) since time \( t = 0 \) is given by following Equation 3.7

\[
p(t) = -\frac{Q}{\sigma_1} (1 - e^{-\sigma_1 t / K_1})
\]

(3.7)

If reservoir has more than one-tank which called N tanks, the pressure response of open lumped model with constant production and since time \( t = 0 \) is given by the Equation 3.8

\[
p(t) = -\sum_{j=1}^{N} Q \frac{A_j}{L_j} (1 - e^{-L_j t})
\]

(3.8)

If reservoir has \( N \) tanks at the same time closed model, then Equation 3.8 should be upgraded new equation is given in Equation 3.9

\[
p(t) = -\sum_{j=1}^{N} Q \frac{A_j}{L_j} (1 - e^{-L_j t}) - QBt
\]

(3.9)

The coefficients \( A_j, L_j \) and \( B \) are functions of the storage coefficients of the tanks \( (\kappa_i) \). In addition that, \( A_j \)'s may be called amplitude coefficients, and term of \( L_j \)'s are eigenvalues of problem or decay rate coefficients.

It should be mentioned data that collected in reservoir will be change the source of measurement. Which means observed water level or pressure is measured in a production well, the water level data must be corrected for turbulence pressure losses in following Equation 3.10, \( C \) represents turbulence coefficient.

\[
p'(t) = p(t) - CQ^2
\]

(3.10)

The data that is simulated is selected and loaded into Lumpfit software. Then the properties of the data that are to be simulated are selected such as measurement type, depth below surface, production sign, conversion factors and time unit. The program automatically makes a first guess for the model coefficients. Also, software changes the parameters b automatic iterative process until best fit for the model selected gained. If Lumpfit cannot successfully fit data, the user will have to adjust their initial guess of the parameter. After the best fit model is obtained, the parameters of the model can be used to estimate the properties of the reservoir and to predict pressure changes in the reservoir for scenarios taking into account given properties.

The coefficients \( A_n, L_n \) and \( B \) are functions of the storage coefficients of the tanks \( (\kappa_j) \). Also, \( A_n \)'s may be called amplitude coefficients and the term of \( L_n \)'s are eigenvalues of problem or decay rate coefficients. Parameters and properties represented above changes respect to number of the tank model. \( K_n \) represent coefficient of tank mass storage, \( \sigma_1 \) represents mass conductance of resistor and \( V_n \) represents volume of the reservoir. As already mentioned above \( A_i, L_i \) and \( B \) are the functions of the storage coefficients of the tanks.
and the conductance coefficients of resistors $\sigma_j$ of the model. Storage coefficient of a tank is defined by following Equation 3.11

$$k_i = V_i s$$  \hspace{1cm} (3.11)

Where $s$ is the storability and $V_i$ the volume of a tank. For two-dimensional flow the average permeability, $k$, can be estimated by using the Equation 3.12-3.14:

$$k = \frac{\sigma}{2\pi} \ln \left( \frac{r_2}{r_1} \right) \nu$$  \hspace{1cm} (3.12)

$$r_1 = \frac{R_1}{2}, \quad r_2 = R_1 + \frac{R_2 - R_1}{2}, \quad r_3 = R_1 + \frac{R_3 - R_2}{2}$$  \hspace{1cm} (3.13)

$$R_1 = \sqrt{\frac{V_1}{\pi H}}, \quad R_2 = \sqrt{\frac{V_1 + V_2}{\pi H}}, \quad R_3 = \sqrt{\frac{V_1 + V_2 + V_3}{\pi H}}$$  \hspace{1cm} (3.14)

Equations 3.7-3.14 will be used to calculate water level, permeability, storage mechanism, size and other crucial properties of the reservoir.

### 3.2 Theory of USGS Hydrotherm

USGS Hydrotherm software was published by United States Geological Survey and it simulates thermal energy transport in three-dimensional, two-phase, hydrothermal, groundwater flow systems. It can handle fluid temperatures up to 1,200 degrees Celsius ($^\circ$C) and fluid pressures up to $1 \times 10^9$ pascals (Pa) which equals to $10^4$ atmospheres (atm). This temperature range covers that of a basaltic-magmatic hydrothermal system and exceeds that of a silicic-magmatic hydrothermal system. Both confined and unconfined ground-water flow conditions can be represented, with unconfined flow including unsaturated zone water flow with uniform atmospheric pressure in the soil air phase. Hydrotherm simulates ground-water flow of only a single fluid component; pure water. The governing partial differential equations, which are solved numerically, these are

- The water-component flow equation formed from the combination of the conservation of mass in the liquid and gas phases with Darcy’s law for flow in porous media.
- The thermal-energy transport equation formed from the conservation of enthalpy for the water component and the porous medium.

These two equations are coupled through the dependence of advective heat transport on the interstitial fluid-velocity field and the dependence of fluid density, viscosity, and saturation on pressure and temperature.
3.2.1 Ground-water flow equation

The following assumptions must be made in order to solve the partial differential equations of the water. These assumptions are summarized below (Hayba & Ingebritsen, 1994) (Ingebritsen & Sanford, 1998).

- The fluid is pure water which can exist in liquid and gas (vapor) phases.
- Flow is described by Darcy’s law for a two-phase system.
- Capillary-pressure effects are negligible in zones of liquid water coexisting with water vapor (one component zones).
- Capillary-pressure effects are represented by non-hysteretic functions of liquid phase saturation in zones of liquid water coexisting with air (two-component zones).
- Relative permeabilities are non-hysteretic functions of liquid phase saturation.
- No dissolved air exists in the liquid phase.
- No water vapor exists in the gas phase in zones where air is present (two-component zones).
- The air component is stagnant with no buoyant circulation.
- The coordinate system is right-handed with the z-axis pointing vertically upward.

Cause and effect relation of these assumptions given by (Hayba & Ingebritsen, 1994; Ingebritsen & Sanford, 1998). In addition that, there is one limitation on the unconfined extension is that HYDROTHERM cannot simulate boiling liquid at the water table (Kipp, Hsieh, & Charlton, 2008). In the light of these assumptions and dependent variable for fluid flow. All pressures are approved as absolute. Water component flow equation which based on the conversation of water mass in a volume element, coupled with Darcy’s law for multiphase flow through a porous medium (Faust & Mercer, February 1979; Huyakorn & Pinder, 1983; Kipp, Hsieh, & Charlton, 2008). Thus:

\[
\frac{\partial}{\partial t} \left[ \phi (\rho_w S_w + \rho_s S_g) \right] - \nabla \times \left( \frac{k_{rw} \rho_w}{\mu_w} [\nabla p + \rho_w g \hat{e}_z] - \nabla \frac{k_{rs} \rho_s}{\mu_s} [\nabla p_g + \rho_s g \hat{e}_z] - q_{sf} \right) = 0
\]

(3.11)

Where \( \phi \) is the porosity (dimensionless), \( \rho \) is the fluid density (kg/m\(^3\)), \( S_w \) saturation of water in phase, \( k_r \) is the relative permeability (dimensionless), \( \mu \) is the viscosity (Pa-s), \( p \) is the fluid pressure in the liquid phase (Pa), \( p_g \) is the fluid pressure in the gas phase (Pa), \( g \) is the gravitational constant (m/s\(^2\)), \( \hat{e}_z \) is the unit vector in the z-coordinate direction (dimensionless), \( q_{sf} \) is the flow-rate intensity of a fluid-mass source (positive is into the region) (kg/s-m\(^3\)), \( t \) is the time (s), and \( \nabla \) is the spatial gradient (m\(^{-1}\)). In addition, \( p_g = p \), because capillary pressure is assumed to be zero. Two components where the air-water is in the unsaturated zone, steam are not presented in Equation 3.11. Because of atmospheric pressure and of negligible density which cause not flowing, there is no flow equation needs to be formulated for air component in unsaturated zone. Due to multi-phase zone of the simulation area, saturation constraint equation is generalized to:

\[
S_w + S_g = 1
\]

(3.12)

Where \( S_w \) is the saturation of the liquid phase (water), and \( S_g \) is the saturation of the gas phase (steam or air). In the light of these assumptions \( S_g \) represents the saturation either water vapor
(steam) or air. Furthermore, there is no provision for steam and air to coexist in the Hydrotherm simulator (Kipp, Hsieh, & Charlton, 2008). Pore velocity of the water component in phase p is obtained from Darcy’s law and shown in Equation 3.13:

$$v_p = -\frac{k k_{rp}}{\phi S_p \mu_p} [\nabla p + p_p g \hat{e}_z]$$

(3.13)

Where \(v_p\) is the interstitial-velocity vector for water in phase p; \(p = \text{w (water) or s(steam)}\) (ms). Water table is assumed atmospheric pressure and form of water table can be determined from the pressure state.

### 3.2.2 Thermal-energy transport equations

The following assumptions must be made in order to solve the partial differential equation of thermal energy transport. These assumptions are summarized below (Hayba & Ingebritsen, 1994; Ingebritsen & Sanford, 1998; Kipp, Hsieh, & Charlton, 2008).

- Heat transport mechanism comprises thermal conduction and advection only.
- Heat transport by dispersion is neglected.
- Heat transport by radiation is neglected.
- The porous matrix and the fluid phases are in thermal equilibrium.
- Heating from viscous dissipation is neglected.
- Convective heat transport by air in the gas phase is neglected.
- Thermal conduction occurs through the liquid, gas, and solid phases in parallel.
- Thermal conductivity is not a function of porosity or liquid saturation.
- Conductive heat transport through the air in the gas phase is approximated by an effective thermal conductivity specified for the solid and liquid phases.
- Thermal conductivity of the porous matrix is a function of spatial location.
- Heat capacity of the porous matrix may be a function of temperature.
- Heat capacity of the air component is neglected.
- Thermal conductivity of the porous matrix may be a function of temperature.
- Enthalpy of the porous matrix is only a function of temperature.
- Thermal expansion of the porous medium is neglected.

Cause and effect relation of these assumptions given by Hayba and Ingebritsen (1994) and Ingebritsen and Sanford (1998). In addition, reports of equilibration times of minutes to hours (Quantitative hydrogeology, groundwater hydrology for engineers) written by de Marsily (1989).

Errors that incurred due to needing to maintain values between thermal conductivity of a porous medium and liquid saturation may be evaluated through this parameter can change by a factor pf 1.2 to 6 for a typical porous media (sand) from residual saturation to full saturation (de Marsily, 1986). Thermal transport equation is based conversation of enthalpy which included fluid and solid phase of porous medium in a volume element of the region. Enthalpy is derived property having both energy and flow energy which represented by following Equation 3.14

$$\frac{\partial}{\partial t} [\phi (\rho_w h_w S_w + \rho_s h_s S_s) + (1 - \phi) \rho_r h_r] - \nabla \times K_a \nabla T + \nabla \times (\phi (S_w \rho_w h_w v_s) - q_{sh}) = 0$$

(3.14)
Where \( h \) is the specific enthalpy of the fluid phase (j/kg), \( h_r \) is the specific enthalpy of the porous-matrix solid phase (rock or sediment) (kg/m\(^3\)), \( p_r \) is the density of the porous-matrix solid phase (rock or sediment) (kg/m\(^3\)), \( K_a \) is the effective thermal conductivity of the bulk porous medium which combined liquid, gas, and solid phases (W/m\(^\circ\)C), \( I \) is the identity matrix of rank 3 (dimensionless), \( q_{sh} \) is the flow-rate intensity of an enthalpy source which positive is into the region (W/m\(^3\)). The subscripts of w and s refer to water and steam respectively. All the equations located in section 3.2.1 and 3.2.2 taken from (Hayba & Ingebritsen, 1994; Ingebritsen & Sanford, 1998; Kipp, Hsieh, & Charlton, 2008; de Marsily, 1986) and detailed derivation of Equation 3.14 given by (Huyakorn & Pinder, 1983; Faust & Mercer, 1977).
Chapter 4

Case Study

Methods that were presented in section 3 are applied to Munadarnes low temperature geothermal systems in west Iceland. Changes in water level and production history of geothermal areas are used to compute sustainable production limit for case study. The guide followed in the case study is given schematically at Figure 4-1.

**Figure 4-1:** Schematic representation of the steps taken to estimate the sustainable production limit of the Munadarnes reservoir.

In order to achieve the sustainable production limit of the Munadarnes low temperature geothermal reservoir, 4 different lumped tank models with various flow rates were simulated. The same flow rates were used to simulate the application of reinjection with 2 different flow regimes. At the end the respond to the reservoir was analyzed according to this data.
4.1 Munadarnes geothermal area

Munadarnes geothermal area is located a distance of 91 km north-northeast from Reykjavik and has been supplying hot water via MN-08 well with average water temperature of 87.3 °C since 2004. Figure 4-2 represents an overview of Munadarnesveita. Total utilization in 2017 was over than 220000 m³ and overall production since 2005 is over 2.6 million m³ with average flow rate of 10 l/s hot water supplied to district heating applications for 160 facilities that located close by. In addition, Munadarnes geothermal reservoir positioned Nordurardalur geothermal field and this geothermal field located Borgarfjordur geothermal region in west Iceland.

![Figure 4-2: Overview of Munaðarnesveita taken from (Olsen, 2014).](image)

Average water level level is 25.0 meter below the sea level and geothermal water is supplied via MN-08 borehole which is drilled in 2003 and 900 meters below than surface. Overview of the geothermal system is represented in following Table 4-1.

### Table 4-1: Overview of the operation of the Munurarnes.

<table>
<thead>
<tr>
<th>Borehole</th>
<th>Drilled</th>
<th>Depth m</th>
<th>Temperature °C</th>
<th>Casing m</th>
<th>Production casing</th>
<th>Pump type</th>
<th>Pump pipe size</th>
<th>Motor rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>MN-08</td>
<td>2003</td>
<td>900</td>
<td>87</td>
<td>149.4</td>
<td>10 ¾</td>
<td>8 JKM</td>
<td>6”</td>
<td>1450</td>
</tr>
</tbody>
</table>
Data collection of system is almost continuous with the exception from 9 months of 2009 data loss. Average data collection is 5 times in a month and flow rate (l/s), pressure (bar) and depth of water (m) were recorded by provider. There are typing errors, including errors due to malfunctions, obvious errors have been removed from the data. Depth to the water level is calculated from the measured pressure in the air tube along the pump. Figure 4-3 shows the annual production of the Munaðarnesveitu in the period of 2005-2017. Based on graph, production rate tends to increase until 2011 respect to step-wise development and tend to decrease the production between 2011 and 2014. The decline in production is corresponded to 3% between 2012 and 2014. End of the 2014, production limit started to increase again and greatest production rate which is 219 000m³ has been recorded end of the 2017. It should be mentioned that, until 2011 production limits tend to increase by following stepwise development.

![Figure 4-3: Annual Processing of Munaðarnesveitu. End of the 2014 production limit tend to increase again and greatest production rate which is 219 thousand m³ has been recorded end of the 2017. It should be mentioned that, until 2011 production limits tend to increase by following stepwise development.](image)

To understand to decrease on the annual production between beginning of the 2012 and end of the 2014 can be explained as pressure differences in MN-08 bore hole. Following Figure 4-4 represents production vs pressure distribution of Munaðarnesveitu field. As can be seen here pressure of the borehole is reduced in a controlled manner to maintain production rate. Highest average pressure values was recorded in 2014 which is 7.89 bar. By the end of the 2014, pressure was reduced in a controlled manner to reach new equilibrium in MN-08. Greatest annual production which is 220 000 m³ has been recorded at 2017 also, lowest pressure recorded at same year since beginning of the process.
Figure 4-4: As can be seen here pressure of the borehole is reduced in a controlled manner to maintain production rate. Highest average pressure value has been recorded in 20014 which is 7.89 bar. End of the 2014 pressure is reduced in a controlled manner to reach new equilibrium in MN-08. Greatest annual production which is 220,000 m$^3$ has been recorded at 2017 and lowest pressure recorded at same year since beginning of the process.

In addition, chemical content of water such as CO$_2$, H$_2$S, Cl, Na, SO$_2$ t-icp etc. has been recorded since beginning of production process and content of the water which extracted via MN-08 hole has been stable over the period 2003-2017. Figure 4-5 represents temperature measurements from 2007 to 2017, as already mentioned before MN-08 borehole have been operating to discharge geothermal water without reinjection operation. Measurements made over 10 years showed that water level in MN-08 slightly decrease except seasonal variation on flowrate. During the winter season see the highest decrease in water level due to natural recharge reservoir has been success to recover water level without reinjection. In the light of this information structure that located from surface to reservoir has a great porosity and permeability.

Figure 4-5: Testing and measurement from 2007 clearly shows that there is no significant temperature change recorded up to 2017.
4.2 Geological, geophysical and hydrological settings

Tertiary aged basaltic magma has been located as a bedrock and constituted the Borgarfjodur region. Oldest rock that comprises these lava flows being 14-15 Myrs and characterized by a uniform lithology. Tholeiitic basaltic lava has been formed bulk of tertiary lava flows. As can be expected geophysics of the region formed by the volcanism which is resulted divergent boundary from tensional stress in the earth crust. Nordurardalur geothermal system which comprised Munadarnes geothermal reservoir is confined within the WNW-ESE, N-S fractures zone and between the Hredavatn unconformity and the Borganes anticline (Saemundsson, 1979). Origin of the water is meteoric and by result of precipitation on Nordurardalur area. Thanks to gravity force water flowing through fractures, cracks and pathways that located as layers from surface to reservoir and heated by regional heat flow. Due to Northeasterly faults which called main channels to percolates for Nordurardalur thermal system and provided by seismicity in the region.

Heat is transferred by conduction through the Earth’s crust from the Snaefellsnes volcanic flank zone and the Reykjanes-Langjokull volcanic rift zone. Heat is transferred by the hot water though the fracture and fault systems at depth. The thermal energy comes also from depth. The thermal energy transferred by the geothermal activity also comes from stored energy around the fractures, generally in the crust, specifically in extinct central volcanoes (Achou, 2016).

According to stimulation and measurement in well MN8 Munadarnes technical report that prepared for Orkuveita Reykjavíkur by Iceland Geosurvey (ISOR) temperature gradient of region is 250 °C/km and convective parts starts between 430-450 meters and continues at least 900 meters (Saemundsson, Hjartarson, & Bjornsson). Also, by taking advantage of temperature measurement thickness of reservoir estimated at least 450 m.

4.3 Lumped parameter modelling of MN-08

Water level, pressure and production rate has been monitored for the well since January 2007 with data up to December 2017 supplied by Reykjavik Energy for this thesis. Whereas, well MN08 was drilled in 2003 with 35-meter initial water level. It should be mentioned that, there are nine months missing data from January to September 2009. The data consisted of water level measurement in m, pressure measurement in barg with corresponding flow rate in l/s measurement date. Furthermore, approximately 508 measurements were recorded, however, 154 measurements have been simulated. This is because, measurement period was not increase monotonically. The reason for the using the data is define initial and crucial parameters of the reservoir and appoint sustainable production limit. Equations that mentioned in section 3.1.1 will be used to predict water level and pressure change in reservoir. Figure 4-6 shows water level range and simulation results from LUMPFIT V3 with two tank open model from January 2007 to December 2017. All the lumped tank models have been simulated. Best fitting model and properties of reservoir are found in two tank open model.

However, the fit that was obtained in the 3 tank closed and 3 tank open models was quite similar the fit that was obtained from 2 tanks open model. Moreover, properties of the first and second tank in 2 tanks open and 3 tanks models were almost same, but properties of the third tank was not logical when compared with the thermal region of Borgarfjordur. Reservoirs consists of the central part which is the main part of production and second tank (outer part of reservoir) which can be called aquifer has a great permeability to flow-feed central part of reservoir. The second tank is connected by a resistor to a constant pressure source which supplies recharge to the geothermal system (open system). Due to constant
pressure source, water prediction that was simulated by LUMPFIT V3 will be optimistic for scenario of 2 tanks open model. Following Table 4-2 shows the estimation of the physical parameters that obtained from simulating water level and production rate for 11 years data. Table 4-3 represents reservoir properties that was estimated based on parameters computed. As mentioned before, reservoir properties of the 3 tank models obtained by Lumpfit V3 are quite acceptable except they cover an area of approximately 500 km². However, this model results in a root mean square error which is greater than the other tank models. Which indicates that distance difference between models, in other words how much a model disagrees with the actual data. It shows that, Munadarnes reservoir may be has 3 tanks but the third tank is not connected to the system.

Table 4-2: Parameters of the lumped models for the production well MN08 in Munardanes.

<table>
<thead>
<tr>
<th>Model number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of tanks</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Number of parameters</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Model types</td>
<td>Closed</td>
<td>open</td>
<td>Closed</td>
<td>Open</td>
<td>Closed</td>
<td>Open</td>
</tr>
<tr>
<td>$A_1(10^6)$</td>
<td>0</td>
<td>4.10</td>
<td>4.12</td>
<td>5.55</td>
<td>5.78</td>
<td>5.79</td>
</tr>
<tr>
<td>$L_1(10^3)$</td>
<td>0</td>
<td>3.21</td>
<td>3.45</td>
<td>6.59</td>
<td>7.12</td>
<td>7.14</td>
</tr>
<tr>
<td>$A_2(10^7)$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>83.30</td>
<td>1.12</td>
<td>1.13</td>
</tr>
<tr>
<td>$L_2(10^4)$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.84</td>
<td>2.66</td>
<td>2.70</td>
</tr>
<tr>
<td>$B(10^5)$</td>
<td>4.35</td>
<td>0</td>
<td>34.29</td>
<td>0</td>
<td>19.58</td>
<td>0</td>
</tr>
<tr>
<td>$K_1(Kg/Pa)$</td>
<td>2420</td>
<td>25.65</td>
<td>25.51</td>
<td>18.67</td>
<td>17.84</td>
<td>17.80</td>
</tr>
<tr>
<td>$K_2(Kg/Pa)$</td>
<td>0</td>
<td>0</td>
<td>30671.46</td>
<td>1322.78</td>
<td>976.23</td>
<td>966.34</td>
</tr>
<tr>
<td>$K_3(Kg/Pa)$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>52764.68</td>
<td>47063.12</td>
<td></td>
</tr>
<tr>
<td>$\sigma 1(10^6)$</td>
<td>0</td>
<td>8.23</td>
<td>8.82</td>
<td>12.14</td>
<td>12.48</td>
<td>12.48</td>
</tr>
<tr>
<td>$\sigma 2(10^6)$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>24.67</td>
<td>25.98</td>
<td>26.10</td>
</tr>
<tr>
<td>$\sigma 3(10^6)$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>25.90</td>
</tr>
<tr>
<td>RMS(m)</td>
<td>30.68</td>
<td>4.18</td>
<td>3.44</td>
<td>1.97</td>
<td>1.81</td>
<td>1.81</td>
</tr>
<tr>
<td>STD(m)</td>
<td>31</td>
<td>4.18</td>
<td>3.44</td>
<td>1.97</td>
<td>1.9</td>
<td>1.9</td>
</tr>
<tr>
<td>DF</td>
<td>123</td>
<td>122</td>
<td>121</td>
<td>120</td>
<td>119</td>
<td>118</td>
</tr>
</tbody>
</table>
Overall the results from LUMPFIT V3 can be summarized as follows; Due to liquid dominated system, the reservoir can be compressed water. When the reservoir produced, water expands as result of compressibility and this is called confined reservoir. According to simulation results, total area that covered by confined reservoir is 16.1 km$^2$ which is comparable to thermal region of Borgarfjordur (300 km$^2$), the largest low temperature area in Iceland (Kristmannsdóttir, Björnsson, Arnórsson, Ármannsson, & Sveinbjörnsdóttir, 2005; Georgsson, Johannesson, & Bjarnason, 2010) d. Assuming two-dimensional flow and a reservoir thickness of 0.9 km and based on equations (3.12-13-14) reservoir permeability is estimated about 1.62 mDarcy. Following Table 4-3 represent detailed reservoir properties of Munadarnes reservoir.

### Table 4-3: Properties of Munadarnes reservoir calculated by Lumpfit V3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>87.00 °C</td>
</tr>
<tr>
<td>Density</td>
<td>967.30 kg/m$^3$</td>
</tr>
<tr>
<td>Thickness</td>
<td>900.000000 m</td>
</tr>
<tr>
<td>Porosity</td>
<td>15.00%</td>
</tr>
<tr>
<td>Kinematic Viscosity</td>
<td>3.4e-07 m$^2$/s</td>
</tr>
<tr>
<td>Fluid Compressibility</td>
<td>4.7e-10 1/Pa</td>
</tr>
<tr>
<td>Rock Compressibility</td>
<td>3e-11 1/Pa</td>
</tr>
<tr>
<td>Total Compressibility</td>
<td>9.6e-10 1/Pa</td>
</tr>
<tr>
<td>Unconfined Storativity</td>
<td>1.7e-05 kg/m$^3$/Pa</td>
</tr>
<tr>
<td>Confined Storativity</td>
<td>9.3e-08 kg/m$^3$/Pa</td>
</tr>
</tbody>
</table>

Figure 4-6: Two tank open model LUMPFIT V3 simulation result of water level data from January 2007 to December 2017. Green lines represent production values that recorded selected time period, blue points represent measured water level from well, red line represent 2 tanks open model.
4.4 Water level prediction scenarios of MN-08

According to results that shown in Table 4-2 and Equation 3.9, predicted water level for the system has been calculated. Eight different scenarios for each lumped tank models are predicted 6.3, 7.3, 9.3 and 12.3 kg/s flow rate respectively. Figure 4-7 represents 20 years predictions without reinjection while, Figure 4-8 represents same scenario with reinjection. Efficiency of reinjection operation assumed 100% which represents the injected water mass has successfully reached the reservoir via reinjection well. According to 5 kg/s and 7 kg/s constant reinjection rate, in both scenarios expected water levels quite different than without reinjection scenarios. As can be expected, reinjection scenarios can affect the reservoir state. Such as, cooling of reservoir, boiling affect and change in chemical content of the geothermal water.

![20 Years predictions for all lumped models with flow rate of 6.3 kg/s](image)

**Figure 4-7**: 20 years water level prediction for well MN08 flow rate of 6.3 kg/s, without reinjection. Blue line represents 2 tank closed, red line represents 2 tank open, green line represents 3 tank closed and purple line represents 3 tank open model.

The average extraction rate of the Munadarnes reservoir in 2017 is 8.3 kg/s. In this scenario, however, the production rate was chosen to be 6.3 kg/s. Due to the decrease in production flow, a rise in water level was detected at the beginning of the 6.3 kg/s scenarios.
Figure 4-8: 20 years water level prediction for well MN08 with re-injection rate of 5.0 kg/s. Blue line represents 2 tank closed, red line represents 2 tank open, green line represents 3 tank closed and purple line represents 3 tank open model.

As can be seen in Figure 4-7 with respect to a constant flow rate of 6.3 kg/s, no significant drawdown was detected. But significant change in water level has been detected 2 tank closed model. As mentioned before closed tank model will be represented pessimistic scenario of given flow rate. Expected change in water level is more than 13 meters for 20 years 2 tank closed model prediction. This can be called the maximum drawdown for a flow rate of 6.5 kg/s. 2 tank open model is the optimistic future prediction for flow rate of 6.5 kg/s. In addition, calculated average flow rate from 2007 to 2017 is 6.3 kg/s and we build first scenario considering the average flow rate of the Munadarnes reservoir. Figure 4-9 represent second scenario with flow rate of 7.3 kg/s while, Figure 4-10 represents same scenario with reinjection rate of 5 kg/s.
20 years water level prediction for well MN08 flow rate of 7.3 kg/s, without reinjection. The greatest drawdown was found in the 2 tanks which were the same as the previous scenario.

Figure 4-10: 20 years predictions production rate of 7.3 kg/s with reinjection rate of 5 kg/s.

The second scenario showed that the expected drawdown in flow rate of 7.3 kg/s was more than flow rate of 6.3 kg/s. Overall result of second scenario is same as first scenario in perspective of tank models. 2 tank open model is optimistic than the other models and 2 tank closed model pessimistic than rest of the models. Greatest drawdown is detected in the 2 tank closed model which is more than 15 meters and over the period of 20 years. Following Figure 4-11 represent second scenario with flow rate of 9.3 kg/s while, Figure 4-12 represents same scenario with reinjection rate of 5 kg/s.
Due to increase in flow rate, third scenario starts at drawdown, but the reservoirs reach an equilibrium and drawdown continuous in a balanced manner.

Figure 4-11: 20 years predictions production rate of 9.3 kg/s without reinjection. Due to increase in flow rate, third scenario starts at drawdown, but the reservoirs reach an equilibrium and drawdown continuous in a balanced manner.

Figure 4-12: 20 years predictions production rate of 9.3 kg/s with reinjection rate of 5 kg/s.

Due to increase in flow rate, the third scenario starts at drawdown, but the reservoirs reach an equilibrium and drawdown continuous in a balanced manner. The 2 tank closed model has the largest decline end of the 20 years which is more than 30 meters. It should be mentioned that, 2 tank open, 3 tank closed and 3 tank open curves tend to be more optimistic than the 2 tank closed model, with trends close to each other. By taking advantage of the reinjection, drawdown of the reservoir can be controlled, and utilization of the system...
continued in a sustainable manner. Greatest drawdown detected flow rate of 12.3 kg/s represented at Figure 4-13, and Figure 4-14 represents same scenario with 5 kg/s reinjection.

**Figure 4-13:** 20 years predictions production rate of 12.3 kg/s without reinjection. The greatest decrease in water level was detected at a flow rate of 12.3 kg/s.

**Figure 4-14:** 20 years predictions production rate of 12.3 kg/s with reinjection rate of 5 kg/s. Blue line represents 2 tank closed, red line represents 2 tank open, green line represents 3 tank closed and purple line represents 3 tank open model.
Figure 4-15: Water level predicted 20 years without reinjection. 6.3 kg/s represents average flow rate of the Munadarnes reservoir operation time from 2007 to 2017. Rest of the flow rates were increased by 15%, 30% and 32%, respectively, compared to the previous value. 4 flow rates and 4 models are represented above.

As can be seen in the Figure 4-15 the sort of the groups is organized into (from top to bottom) 2 tank open, 3 tank open, 3 tank closed and 2 tank closed model with 6.3 kg/s, 7.3 kg/s, 9.3 kg/s and 12.3 kg/s respectively. Classifying groups according to flow rates will make the graph more understandable. First group distribution of 6.3 kg/s flow rate with all lumped models. Second group distribution of 7.3 kg/s. third group representation of the water level respect to flow rate of 9.3 kg/s and last group representation of the 12.3 kg/s production rate for 20 years operation time. Table 4-4 represents summarization of water level change in MN-08 bore hole.
Table 4-4: Summarization of water level predictions.

<table>
<thead>
<tr>
<th>Flow Rates (kg/s)</th>
<th>Water Level (m) without reinjection</th>
<th>Water Level (m) With 5 kg/s Reinjection</th>
<th>Water Level (m) With 9 kg/s Reinjection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 Open</td>
<td>2 Closed</td>
<td>3 Open</td>
</tr>
<tr>
<td>6.3</td>
<td>-32.22</td>
<td>-20.47</td>
<td>-37.94</td>
</tr>
<tr>
<td>7.3</td>
<td>-35.05</td>
<td>-33.42</td>
<td>-40.19</td>
</tr>
<tr>
<td>9.3</td>
<td>-40.69</td>
<td>-59.29</td>
<td>-44.7</td>
</tr>
<tr>
<td>12.3</td>
<td>-49.11</td>
<td>-98.06</td>
<td>-51.42</td>
</tr>
</tbody>
</table>

4.5 USGS Hydrotherm model of MN-08

Reservoir modeling of the Munadarnes geothermal resource was carried out using software of USGS HYDROTHERM. In light of LUMPFIT V3, the area of reservoir has been modelled to be ~16 km². 2D model of Munadarnes reservoir is shown in Figure 4-16. The length of the x-axis is 9.5cm which equal to 9.5km and z-axis is 1.7cm which equal to 1.7km. Top boundary of reservoir is represented with blue color and bottom boundary of reservoir is shown yellow color. Numbers with straight lines represent temperature and pressure gradient of reservoir. Red points denote injection and re-injection in the well, respectively. The gray colored area scattered along the reservoir represents the basalt which called host rock.

Figure 4-16: 2D representation of Munadarnes Geothermal Reservoir.

Model options for the Munadarnes reservoir are: initial pressure and temperature selected specify graphically, factor for increasing time step is 1.8, maximum iterations per
time step is 30 and relative permeability selected linear. The modeling was done for a total of 32 years for 2 periods; first period simulates 12 years with constant production rate of 6.3 kg/s whereas second period constant production rate of 7.3 kg/s, 9.3 kg/s and 12.3 kg/s flowrate of reinjection scenarios for 20 years. Detailed properties of reservoir are shown in Table 4-5.

**Table 4-5: Reservoir properties of Munadarnes reservoir.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>0.15</td>
</tr>
<tr>
<td>X permeability (m$^2$)</td>
<td>$1.6 \times 10^{-15}$</td>
</tr>
<tr>
<td>Z permeability (m$^2$)</td>
<td>$1.6 \times 10^{-15}$</td>
</tr>
<tr>
<td>Thermal conductivity (W/m-K)</td>
<td>2.0</td>
</tr>
<tr>
<td>Specific heat of rock (KJ/Kg-K)</td>
<td>1.0</td>
</tr>
<tr>
<td>Rock density (kg/m$^3$)</td>
<td>3050.0</td>
</tr>
<tr>
<td>Rock compressibility (bar$^{-1}$)</td>
<td>$3.3 \times 10^{-14}$</td>
</tr>
<tr>
<td>Rock Compressibility</td>
<td>3e-10 /Pa</td>
</tr>
<tr>
<td>Simulation period (year)</td>
<td>25</td>
</tr>
<tr>
<td>Initial time step size (year)</td>
<td>0.1</td>
</tr>
<tr>
<td>Bottom boundary basal heat flux (mW/m$^2$)</td>
<td>63.0</td>
</tr>
<tr>
<td>Pressure of top boundary (bar)</td>
<td>1.01</td>
</tr>
<tr>
<td>Temperature of top boundary (°C)</td>
<td>10</td>
</tr>
</tbody>
</table>

Porosity of the host rock was assumed to be 15%, permeability of the system, rock compressibility calculated by Lumpfit V3. Thermal conductivity and specific heat of rock also assumed. Top boundary conditions selected specify graphically which means pressure of top boundary atmospheric and average temperature. Bottom boundary conditions selected basal heat flux and calculated by equation 4.1 which called Fourier’s law.

$$Q = -k \frac{dT}{dx}$$

(4.1)

Where $Q$ is the heat flux (W/m$^2$) in the positive x-direction, $dT/dx$ is the (negative) temperature gradient (K/m) in the direction of heat flow and the proportionality constant $k$ is the thermal conductivity, Fourier’s Law thus provides the definition of thermal conductivity and forms the basis of many methods of determining its value. Fourier’s Law, as the basic rate equation of the conduction process, when combined with the principle of conservation of energy (Haenel, Stegena, & Rybach, 1988).

Figure 4-17 represents the 2D Munadarnes geothermal reservoir settings, while Figure 4-18 represents 3D model by given properties at Table 4-5 drawing axes X and Z are 3, 9 km respectively and color differences represent temperature distribution of reservoir. Arrows represent liquid water mass flow vectors. In the frame of the scenario created production well is located at a distance of about 2 km from reinjection well and assuming depth of 900 meter. Scenarios were simulated in 4 different production limits within the first 12-year period.
In the second period of 20 years, 2 different rejection limits and temperatures were simulated. Apart from these, in the 32 years period, 4 different production limits were carried out with non-injection simulations. In the frame of the scenario created production well is located at a distance of about 2 km from reinjection well and assuming depth of 900 meter. Scenarios were simulated in 4 different production limits within the first 12-year period. In the second period of 20 years, 2 different ejection limits and temperatures were simulated. Apart from these, in the 32 years period, 4 different production limits were carried out with non-injection simulations.

Figure 4-17: Liquid water mass flow vectors and temperature gradient profile Munadernes Geothermal Reservoir. The color scale on the right side of the graph indicates the temperature distribution of the reservoir and is given in °C.

This scenario resulted in a production well located at a distance of about 2 km from reinjection well and assuming depth of 900 meter. Scenarios were simulated in 4 different production limits within the first 12-year period. In the second period of 20 years, 2 different ejection limits and temperatures were simulated. Apart from these, in the 32 years period, 4 different production limits were carried out with non-injection simulations. Production rates used for all created scenarios are fixed.

Figure 4-18: 3D Liquid water mass flow vectors and temperature gradient profile Munadarnes Geothermal Reservoir
These are: 6.3, 7.3, 9.3, 12.3 kg/s production flow rate and 5.0, 9.0 kg/s reinjection flow rate. Figure 4-19 represent 32 years period with constant production rate of 6.3 kg/s. For this scenario reinjection operation ignored and the response of the reservoir was explored according to the given data.

Figure 4-19: 6.5 kg/s production for 32 years. The color scale on the right side of the graph indicates the temperature distribution of the reservoir and is given in °C.

There is no any significant change in reservoir detected the simulation period of 32 years. Due to flow rate of 6.3 kg/s water mass flux vectors located inside the production well. Negligible change in temperatures contours was detected. Figure 4-20 represent same scenario with 7.3 kg/s flow rate.

Figure 4-20: Flow rate of 6.3 kg/s for first period and flow rate of 7.3 kg/s for second period. The color scale on the right side of the graph indicates the temperature distribution of the reservoir and is given in °C.

This scenario consists of 2 production periods, the first period is 6.3 kg/s flow rate for first 12 years and the second period is 7.3 kg/s for 20 years. Results that were obtained from Figure 4-20Figure 4-7 are exactly same as scenario of 6.3 kg/s production for 32 years. Figure 4-21 represents 2 simulation periods first period is same as previous and second period is 9.3 kg/s production for 20 years.

Figure 4-21: Flow rate of 6.3 kg/s first period and flow rate of 9.3 kg/s second period.
Scenario that production limit of 9.3 kg/s is simulated significant change is detected water mass flux vector. Due to the increase on production limit number of water mass flux vector increased and small change in temperature contours has been detected. Figure 4-22 represents last scenario for without reinjection progress. In this scenario, the first period’s production were modelled with a flow rate of 6.3 kg/s while the second period 12.3 kg/s.

Figure 4-22: Flow rate of 6.3 kg/s for first period and flow rate of 12.3 kg/s for second period.

At the end of the 20 years of production, flow rate was modelled to be 12.3 kg/s without reinjection with small changes in temperature contours. Also, a significant increase on water mass flow vectors was seen. Because of the 12.3 kg/s production, a number of water mass vectors tend to increase. Temperature predictions for first scenario of without reinjection are shown in Figure 4-23. The blue line represents production flow rate of 6.3 kg/s for 32 years. Purple represents first 12 years production flow rate of 6.3 kg/s and 7.3 kg/s for 20 years. Red represents first 12 years production flow rate of 6.3 kg/s and 9.3 kg/s for next 20 years. Green represents 6.3 kg/s flow rate for first period of 12 years and 12.3 kg/s flow rate for second period of 20 years

Figure 4-23: Temperature predictions for first scenario calculated by USGS Hydrotherm (some colors may not appear due to the closeness of the data in the graphic).
The end of the modelled scenario without reinjection scenario temperature gradient of the MN-08 is showed above. Results that obtained this scenario showed that; 6.3 kg/s and 7.3 kg/s production rates have almost same temperature curve end of the 20 years future prediction. At the highest production level, flow rate 12.3 kg/s, the temperature of the reservoir increased at the beginning of the second period and detected the highest decrease at the end of the same period. Figure 4-24 represents constant flow rate of 6.3 kg/s for both period and 5 kg/s reinjection with reinjection temperature of 25°C. Reinjection operation started at second period of the simulation which after the 12 years period. Reinjection well located 2 km away from production well.

Figure 4-24: Simulation result for flow rate of 6.3 kg/s and reinjection rate of 5.0 kg/s. The color scale on the right side of the graph indicates the temperature distribution of the reservoir and is given in °C.

At the end of the 32 years utilization with 5 kg/s reinjection, a cold front was detected inside of the reinjection well. Also, waving on the temperature contours was recorded during the simulation period. Water mass flux vectors that were located between injection and reinjection wells tend to increase from reinjection to injection well. Figure 4-25 represents production flow rate of 7.3 kg/s and reinjection rate of 5 kg/s 20 years simulation.

Figure 4-25: Simulation results production flow rate of 7.3 kg/s and reinjection rate of 5.0 kg/s. The color scale on the right side of the graph indicates the temperature distribution of the reservoir and is given in °C.

The size of the cold front detected was same as last scenario with waving on the temperature contours similar as well. Due to increase on production flow rate, number of water mass flux vectors more than last scenario. In the next scenario, first period which is 12 years production flow rate of 6.3 kg/s and second period which is 20 years production flow rate of 9.3 kg/s with reinjection rate of 5.0 kg/s was simulated and represented at Figure 4-26.
Figure 4-26: Simulation results production flow rate of 9.3 kg/s and reinjection rate of 5.0 kg/s. The color scale on the right side of the graph indicates the temperature distribution of the reservoir and is given in °C.

Scenario production limit of 9.3 kg/s is simulated, and a significant change in water mass flux vector are detected. Depending on the increase in the production limit, the water mass flow vector was increased and waving in temperature contours have been detected. There is no change recorded cold front that located reinjection well. In the next scenario, first period which is 12 years production flow rate of 6.3 kg/s and second period which is 20 years production flow rate of 12.3 kg/s with reinjection rate of 5.0 kg/s was simulated and represented at Figure 4-27.

Figure 4-27: Simulation results production flow rate of 12.3 kg/s and reinjection rate of 5.0 kg/s.

In the scenario production flow rate of 12.3 kg/s with 5 kg/s reinjection, the water mass flux vectors that located reservoir tend to concentrate near the injection well. High injection ratio also caused a change in the water flux vectors that were located in the reinjection well. The cold front that located inside of the reinjection occurred in exactly same area with others. But cooling affect is started after 1 year (2019) compared to other scenarios. The cooling effect of the reservoir in respect to utilization time is showed in Figure 4-28. As can be seen in the figure which is located below 2 points decided and located reservoir to see response of the system. One of the points is located inside of the reinjection well while other one is located between injection and reinjection well. Dark blue represents observation point that located reinjection area which have 6.3 kg/s flowrate with 5 kg/s reinjection utilization time of 32 years. Blue represents observation point that located reinjection area which have 6.3 kg/s flowrate with 5 kg/s reinjection utilization time of 32 years. Grey represents observation point that located reinjection area which have 9.3 kg/s flowrate with 5 kg/s reinjection utilization time of 32 years. Light blue represents observation point that located reinjection area which have 12.3 kg/s flowrate with 5 kg/s reinjection utilization time of 32 years.
As can be seen in cooling figure, all the observation points for reinjection flow rate of 5 kg/s have almost same curve. But, 32 years constant injection rate of 6.3 kg/s and 20 years constant injection rate of 7.3 kg/s have been started to cool in 2018 which is 1 year earlier than other flow rates. End of the utilization period temperature of the reservoir greater than flow rates of 9.3, 12.3 kg/s. Following Figure 4-29Figure 4-29 represents scenario of 9 kg/s reinjection rate. In this scenario 9.3 and 12.3 kg/s production rate have been simulated in two different periods. All scenarios have same settings for the first-time period which is 12 years 6.3 kg/s production rate.

Significant changes in temperature contours have been detected in the scenario of 9.3 kg/s production 9.0 kg/s reinjection for end of the simulation period and due to increase in reinjection rate there is another cold front occurred inside of the reinjection well. Simulated temperature value is approximately 41°C at the end of the 32 years utilization of the reservoir. Water mass flux vectors that are located between injection and reinjection wells tend to move from reinjection to injection well. This situation can cause to decrease in temperature of the reservoir at some point. In the next scenario, first period which is 12 years production flow rate of 6.3 kg/s and second period which is 20 years production flow rate of 12.3 kg/s with reinjection rate of 9.0 kg/s was simulated and represented in Figure 4-30Figure 4-30.
Figure 4-30: Simulation results production flow rate of 12.3 kg/s and reinjection rate of 9.0 kg/s. The color scale on the right side of the graph indicates the temperature distribution of the reservoir and is given in °C.

Rate of waving in temperature contours tend to increase. The increase in production rate caused an increase number of water mass flux vectors. Distance between the water mass flux vectors which are located between production and reinjection wells tend to decrease. It shows that, temperature of the reservoir will decrease at some point. End of the 32 years simulation period there is no significant change in temperature recorded. But the cold front that is located inside of the reinjection area tends to increase and the final value of cold front is approximately 40°C. Figure 4-31 represents cooling effect of Munadarnes reservoir utilization period of 32 years with 9.0 kg/s reinjection rate.

Figure 4-31: Cooling effect of reservoir end of the 32 years utilization with 9 kg/s reinjection. All observation points that located between injection and reinjection well have same temperature curve. Also, observation points that positioned reinjection well have exactly same curve up to 2035 (some colors may not appear due to the closeness of the data in the graphic).

Summary of the temperature predictions that simulated in section 4 is shown in Table 4-6. All the scenarios consist of 4 different flowrates. The first scenario simulated without reinjection while the second and third scenarios with reinjection process. 3 different observation points have been placed in the reservoir. These are the inside of the production and reinjection well and the observation point that is located between production and reinjection well.
Table 4-6: Summarization of 30 years USGS Hydrotherm simulation results.

<table>
<thead>
<tr>
<th>Flow Rates</th>
<th>Observed Temperature in injection well</th>
<th>Observed Temperature in observation point*</th>
<th>Observed Temperature in Reinjection Well</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.3</td>
<td>86.73</td>
<td>86.95</td>
<td>-</td>
</tr>
<tr>
<td>7.3</td>
<td>86.73</td>
<td>86.95</td>
<td>-</td>
</tr>
<tr>
<td>9.3</td>
<td>86.7</td>
<td>86.94</td>
<td>-</td>
</tr>
<tr>
<td>12.3</td>
<td>86.71</td>
<td>86.49</td>
<td>-</td>
</tr>
</tbody>
</table>

**Reinjection of 5 kg/s**

<table>
<thead>
<tr>
<th>Flow Rates</th>
<th>Observed Temperature in injection well</th>
<th>Observed Temperature in observation point*</th>
<th>Observed Temperature in Reinjection Well</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.3</td>
<td>86.71</td>
<td>86.96</td>
<td>53.92</td>
</tr>
<tr>
<td>7.3</td>
<td>86.71</td>
<td>86.96</td>
<td>53.92</td>
</tr>
<tr>
<td>9.3</td>
<td>86.70</td>
<td>86.95</td>
<td>52.94</td>
</tr>
<tr>
<td>12.3</td>
<td>86.69</td>
<td>86.95</td>
<td>52.95</td>
</tr>
</tbody>
</table>

**Reinjection of 9 kg/s**

<table>
<thead>
<tr>
<th>Flow Rates</th>
<th>Observed Temperature in injection well</th>
<th>Observed Temperature in observation point*</th>
<th>Observed Temperature in Reinjection Well</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.3</td>
<td>86.70</td>
<td>86.97</td>
<td>40.84</td>
</tr>
<tr>
<td>12.3</td>
<td>86.69</td>
<td>86.96</td>
<td>39.8</td>
</tr>
</tbody>
</table>

*Observation point placed 1 km east of injection well.
Chapter 5

Sustainable Utilization of Munadarnes Reservoir

In this section water level predictions were combined with temperature predictions to provide sustainable utilization for Munadarnes geothermal area in Iceland. The following section 5.1 is for discussing the result of 7.3 and 20.0 kg/s constant flow rate with/without reinjection models and corresponding response of reservoir. Two scenarios were simulated by choosing production limits of 7.3 kg/s and 20.0 kg/s in the information of 6.3 kg/s, which is the average production limit obtained from the 12-year production rate of the Munadarnes reservoir. The reason for choosing the production limit of 7.3 kg/s is that the reservoir is above the average value of 6.3 kg/s between 2015 and 2017. The reason for the selection of the production limit of 20.0 kg/s is to observe the drawdown in case of the highest rate of 9.5 kg/s 100% increase in annual production values.

5.1 Results of sustainability modelling

Simulation resulted in findings that are represented in section 3.3.4 and 3.3.3 are upgraded and simulated for sustainable utilization of Munadarnes geothermal reservoir. According the Lumpfit results, 2 tank open and 3 tank closed model were best fit for the Munadarnes reservoir. In particular, the 2 tank open model gave satisfactory results in terms of reservoir properties. On the other hand, results of 3 tank closed model showed that properties of the first and second tank are similar to results of 2 tank closed model. Estimated volume of the third tank in 3 closed model is approximately 569 km³ which is too large compared to the geothermal field. As mentioned before closed models represents limited or no recharge. In the light of this information there is no any constant pressure source connected third tank. The summarization of the results obtained in the previous sections showed that the 2 tank open model can be used to simulate sustainability of Munadarnes geothermal reservoir. Due to the open model, future estimates of the reservoir will be optimistic. Hence, 3-tank closed model simulated to improve the reliability of the results and anticipate reductions in the water level.

In this section 2 different scenario are predicted for 50 years future predictions. First scenario is constant flowrate of 7.3 kg/s for 50 years. The second scenario is constant flow rate of 20.0 kg/s for 50 years. Reinjection is is used in both scenarios. Water level predictions calculated by Lumpfit V3 and temperature estimation calculated by USGS Hydrotherm. Following Figure 5-1 represents simulation result of 7.3 kg/s flowrate for 50 years utilization.
Figure 5-1: Simulation result of 7.3 kg/s constant production for 50 years utilization. Blue color represents 2 tank open model while red colors represents 3 closed model. End of the 50 years expected maximum drawdown is 20.55 meters for 3 tank closed model. On the other hand, 0.45 meter upward obtained for 2 tank open model. Expected drawdown may be between 55-85 meters.

The simulation result of 20 kg/s flowrate for 50 years utilization represented in Figure 5-2. Due to heavy increase on flow rate this model resulted in a drawdown greater than first scenario. It should be mentioned that, both curves follow the same trend from 2017 to 2025. It represents the new equilibrium that will form the reservoir at the applied flow rate will be reached in 8 years. Figure 5-3 and Figure 5-4 represents same scenarios with 60% reinjection.

Figure 5-2: Simulation result of 20.0 kg/s constant production for 50 years utilization. End of the 50 years expected maximum drawdown is 179.46 meters for 3 tank closed model. On the other hand, 126.83 meters drawdown detected for 2 tank open model. Expected drawdown may be between 127-180 meters
Figure 5-3: Simulation result of 7.3 kg/s constant production with 60% reinjection for 50 years utilization. Blue line represents 2 tank open model while red line represents 3 closed model. End of the 50 years expected maximum drawdown is 16.00 meters for 3 tank closed model. On the other hand, 2 meters upward detected for 2 tank open model. Expected drawdown may be between 50-80 meters below the surface.

Figure 5-4: Simulation result of 20.0 kg/s constant production with 60% reinjection for 50 years utilization. Blue line represents 2 tank open model while red line represents 3 closed model. End of the 50 years expected maximum drawdown is 167.46 meters for 3 tank closed model. On the other hand, 114.83 meters drawdown detected for 2 tank open model. Expected drawdown may be between 115-168 meters below the surface.
The reservoir temperatures were simulated after simulating the changes in water level. Two scenarios are simulated. All scenarios consist of two periods. The first period represents actual average flowrate that have been utilizing since drilled, which is 6.3 kg/s. Second period represents future prediction for 50 years flow rates are 7.3 and 20.0 kg/s with 60% reinjection. Figure 5-5 represents Hydrotherm results for the first scenario.

**Figure 5-5:** Simulation results of 7.5 kg/s average production without reinjection for 50 years utilization. Simulation consist of 2 periods, first period 6.3 kg/s constant production for first 12 year while second period 7.3 kg/s constant production for 50 years. Two observation point placed reservoir, first observation point placed inside of the injection well and second observation point placed 1 km far away from reinjection well. The color scale on the right side of the graph indicates the temperature distribution of the reservoir and is given in °C.

Figure 5-6 represents the same scenario that was discussed above with 60% reinjection rate. Reinjection starts in the second period, which is between 2017 and 2067.

**Figure 5-6:** Simulation results of 7.5 kg/s average production with 60% reinjection for 50 years utilization. Simulation consist of 2 periods, first period 6.3 kg/s constant production for first 12 year while second period 7.3 kg/s constant production with reinjection rate of 60% for 50 years. Three observation point placed reservoir, first observation point placed inside of the injection well, second observation point placed 1 km far away from reinjection well and third point placed inside of the reinjection well. The color scale on the right side of the graph indicates the temperature distribution of the reservoir and is given in °C.

The end of the first scenario with a reinjection rate of 60% cold front occurred inside of the reinjection well. Temperature of reinjection water is 25°C. The temperature value obtained in the injection well is 86.46°C which equals approximately 1°C drop of initial temperature. The end of the simulation temperature value obtained in the reinjection well is 40.65°C. Following Figure 5-7 represents observed temperature value for 50 years future prediction.
Figure 5-7: Observed temperature values for the first scenario. Blue line represents observation point that located injection well. Red line represents observation point which placed between injection and reinjection well. Green line represents observation point that in the reinjection well. Some colors may not appear due to the closeness of the data in the graphic.

As can be seen chart that represented above, temperature of injection well and temperature of reservoir follow the same tend. Following Figure 5-8 represents simulation result of second scenario without reinjection. Due to heavy increase on production rate number of water mass flux vectors tend to increase.

Figure 5-8: Simulation results of 20.0 kg/s average production without reinjection for 50 years utilization. Simulation consist of two periods, first period 6.3 kg/s constant production for first 12 year while second period 20.0 kg/s constant production for 50 years. Two observation point placed reservoir, first observation point placed inside of the injection well and second observation point placed 1 km far away from reinjection well.

There is no significant change in temperature values end of the 50 years future prediction. This represents the temperature value of reservoir will not affect with production rate. This information will be useful for sustainability of reservoir. Following Figure 5-9 represents same scenario with 60% reinjection.
Figure 5-9: Simulation results of 20.0 kg/s average production with 60% reinjection for 50 years utilization. Simulation consist of 2 periods, first period 6.3 kg/s constant production for first 12 year while second period 20.0 kg/s constant production with reinjection rate of 60% for 50 years. Three observation point placed reservoir, first observation point placed inside of the injection well, second observation point placed 1 km far away from reinjection well and third point placed inside of the reinjection well. The color scale on the right side of the graph indicates the temperature distribution of the reservoir and is given in °C.

Due to increase on reinjection rate, the area of cold front increased. Significant changes were detected in the distribution of water mass flux vectors near the injection well. At the end of the simulation period there is no significant change in temperature of injection and reservoir. As can be seen in the figure, the reinjection operation changed position of the water mass flux vectors. By taking advantage of this movement at some point temperature of reservoir will be decrease. The temperature chart of the last scenario is represented in Figure 5-10.

Figure 5-10: Observed temperature values for second scenario. Blue line represents observation point that placed injection well. Red line represents observation point which placed between injection and reinjection well. Green line represents observation point in the reinjection well. Some colors may not appear due to the closeness of the data in the graphic.

At the end of the 50 years production simulation, the observed temperature in reinjection well is approximately 24.5 °C Celsius while, observed temperature in injection well and reservoir slightly drop which is negligible. As mentioned before, increase in the injection rate was not affected the temperature of the Munadarnes geothermal reservoir.
Figure 5-11 represents the expected pressure change in production well in scenario of 7.3 kg/s and 20.0 kg/s for 50 years future prediction. Changes on the pressure values are exactly reflected in change in the water level for first 12 years utilization. In the light of this information, sustainable utilization will be created in the light of changes in the water level. It should be mentioned that, due to lack of information regarding output temperature of water, reinjection temperature is assumed 25°C Celsius. This assumption reflected the pessimistic scenario of temperature changes in reinjection well.

As it is shown Figure 5-11 observed pressure changes from 2005 to 2017 is 2.9 bar, which equals approximately 30 meters (relationship between pressure and water level). From Figure 4-6 measured water level change from 2005 to 2017 is 33.6 meters. Based on this result, USGS simulation is corrected by first utilization period which reflected actual data’s. The observed change in pressure at the end of the 50 years prediction for constant flow rate of 7.3 kg/s is 2.13 bar. Which equals approximately 20 meters. From Figure 5-1, the change in water level observed in 3 tank closed model is 20.55 meters. This represents a change in pressure values that calculated USGS Hydrotherm corresponding with water level changes that calculated by Lumpfit V3. The same equilibrium was not observed in pressure predictions made at a flow rate of 20.0 kg/s. From Figure 5-11 it was observed that a pressure change in the end of 50 years simulation for constant flow rate of 20.0 kg/s is 26.8 bar. Based on Figure 5-2, the expected water level change is 179.35 meters. The pressure change estimates for 20.0 kg/s are not as accurate as the estimates for 7.3 kg/s. Summarization of pressure vs water level changes represented at Table 5-1.
Table 5-1 Summarization of water level changes based on applied models.

<table>
<thead>
<tr>
<th>Model</th>
<th>Average flow rate (kg/s)</th>
<th>Water level changes (meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Tank open</td>
<td>7.3</td>
<td>2.84</td>
</tr>
<tr>
<td></td>
<td>20.0</td>
<td>126.83</td>
</tr>
<tr>
<td>3 Tank Closed</td>
<td>7.3</td>
<td>20.55</td>
</tr>
<tr>
<td></td>
<td>20.0</td>
<td>179.35</td>
</tr>
<tr>
<td>USGS Hydrotherm</td>
<td>7.3</td>
<td>21.72</td>
</tr>
<tr>
<td></td>
<td>20.0</td>
<td>274.2</td>
</tr>
</tbody>
</table>

5.2 Discussions

The best fit and reservoir properties for the Munadarnes reservoir in Table 4-3 and Figure 4-6 were found in the two tank open model. However, the fit that found in three tank closed model exactly same as two tank open model except reservoir properties. Especially, area of third tank was not comparable with Borgarfjordur thermal region which is approximately 300 km². It can be mentioned that the Munadarnes reservoir may have a three tank closed model, as the estimates of the two tank open models are quite optimistic than the other models. Due to a closed tank conditions, Munadar nes low temperature reservoir may be not connected Borgarfjordur thermal region with a constant pressure recharge zone. Three tank closed model predictions can be reflected and simulated to give an idea of the drawdown. Three tank closed model estimates may be closer to the expected drawdown in reservoir.

Based on the simulation results of the two tank open model, the end of the 50 years with constant flow rate of 7.3 kg/s expected water level change is 2.84 meter upflow which is very optimistic. On the other hand, the three tank closed model showed that expected drawdown is 21.41 meters for same settings. Taking advantage of results from past studies, expected range of drawdown can be between 0-30 meters. Clearly shown in Figure 5-7, the end of the 50 years utilization with constant 60% reinjection is 4.4 kg/s with only 2°C declines in temperature was observed.

Based on the simulation results of the two tank open model, the end of the 50 years with constant flow rate of 20.0 kg/s expected drawdown is 126.94 meter which equals 197.34 meters below surface. On the other hand, the three tank closed model shows that a expected drawdown is 179.46 meters which equals 252.33 meters below surface. In the light of these information Munadarnes low temperature reservoir can be utilized (pumped) production rate of 20.0 kg/s with approximately 180.0 meters drawdown. Figure 5-10 shows at the end of the 50 years utilization with constant 60% reinjection of 12.0 kg/s there is no significant temperature change is observed reservoir and injection well.

In the simulation of the sustainability analysis of the Munadarnes reservoir, the reinjection limit was set at 60% of the production limit. The expected drawdown can be reduced in proportion to the success of the re-injection. Re-injection applications were simulated with 20°C injection temperature. As can be seen in Figure 5-7 there is no significant temperature change observed both production well and observation point at the distance of 2 km from reinjection well. This is an effective parameter for determining the distance between production and injection well.
From Table 5-1 and Figure 5-11, clearly proved that water level corresponding to the pressure changed values calculated by USGS Hydrotherm reflected almost same results for first utilization period which have average flow rate of 6.3 kg/s and first scenario of 50 year future predictions for 3 tank closed model with flow rate of 7.3 kg/s. On the other hand, the same matching was not detected at the second scenario flow rate of 20.0 kg/s. Water level corresponding to the pressure changed values that calculated by USGS Hydrotherm was pessimistic than Lumpfit V3 predictions. In the light of this information, general results provided that; water level will be played key role to estimate the sustainable production limit for Munadarnes Reservoir.

The results of the calculations reflected the sustainable production potential of the system is probably slightly more than the present production which between 6.3 and 12.3 kg/s, and the sustainable energy production potential of the Munadarnes system is controlled by pressure decline and the limited size of the thermal water system, rather than by energy content.
Chapter 6

Conclusion

This thesis focused on estimating the sustainability of geothermal reservoirs using Lumpfit V3 and USGS Hydrotherm. These software packages were selected as they are time and cost-effective modeling methods. Basic background about sustainable management and nature of geothermal reservoirs were introduced. Then, the methods that can be followed to achieve a sustainable production limit were introduced. The flow rates, water level changes and geological settings of the MN-08 borehole provided by Reykjavik Energy were simulated with 56 different scenarios to estimate the sustainable production limit of Munadarnes geothermal reservoir.

All the lumped tank models have been simulated. The best fitting model and properties of reservoir are found in two tank open model. However, the fit that was obtained in a three tank closed and three tank open models were quite similar the fit that obtained from two tanks open model. Moreover, properties of the first and second tank in two tanks open and three tanks models were almost same, but properties of the third tank was not comparable with the thermal region of Borgarfjordur. Based on Lumpfit results state of the Munadarnes reservoir is confined and covers an area of 16.1 km². Permeability of the reservoir is estimated at 1.62 mDarcy, depending on the depth of 900 m. Expected changes in water level in the 50-year future prediction for the constant production rate of 7.3 kg/s are 2 m upflow for the two tank open model and 20.55 m drawdown for the 3 tank closed model.

Based on ground-water flow and heat transport results which is simulated by USGS Hydrotherm, there is no significant temperature change was observed in production well at the end of the 50-year future prediction. On the other hand, calculated temperature drop in the reinjection well is 50°C for a constant injection rate of 4.4 kg/s and 60°C for a constant injection rate of 12.0 kg/s. Based on pressure values calculated by USGS Hydrotherm, the change in water level recorded between 2005 and 2017 were corresponding almost the same as pressure values. The water level change is measured from the MN-08 well for the first utilization period is 33.6 meters, which is equal to 3.2 bar and the pressure change calculated by Hydrotherm is 3 bar. The same rate was detected for a 50-year future prediction with a flow rate of 7.3 kg/s. 50 year future pressure estimations made at a flow rate of 20 kg/s were pessimistic than Lumpfit V3 results. The differences between calculations were about 10 bar which is equal to approximately 100 meters.

Based on the water level estimates of the Munadarnes Reservoir calculated by Lumpfit V3, all flow rate scenarios show that the most optimistic estimates are calculated with two tank open models, and the most pessimistic estimates are with two tank closed models. The three tank closed model which located between these two points is verified by the USGS Hydrotherm pressure calculations. On the other side, reservoir area of 3 tank closed model estimated by Lumpfit V3 is greater than thermal region of Borgarfjordur. Due to closed tank conditions third tank of the system may not connected thermal region.
Overall results indicated that the Munadarnes reservoir have been utilized in a sustainable manner with average flow rate of 6.3 kg/s. In the light of Lumpfit v3 and USGS Hydrotherm outputs, Munadarnes reservoir might be utilized in a sustainable manner for 50 years with average flow rate range of 6.3 – 9.3 kg/s and average drawdown of 20.55 – 60.25 meter. By taking advantage of reinjection, the reservoir pressure and water level are increased significantly.

The results of the calculations showed the sustainable production potential of the system is probably slightly more than the present production which between 6.3 and 12.3 kg/s, and the sustainable energy production potential of the Munadarnes system is controlled by pressure decline and the limited size of the thermal water system, rather than by energy content.

This work is limited with low temperature geothermal systems and can be extended with more complex systems and detailed reservoir configuration software’s. Further, more detailed simulations such as Tough2 can be used to estimate the reservoir behavior for the given production limit. Lumpfit V3 software which based on nonlinear iterative least squares technique and developed by ISOR has been used to simulate reservoir conditions. USGS Hydrotherm simulations were created using Lumpfit V3 results. The purpose of using software of USGS Hydrotherm is to create the reservoir geometry which is ignored in the first step and to analyze the response of the reservoir according to the parameters to be applied. Also this thesis, provided a chance to compare the results obtained by Lumpfit V3 and USGS Hydrotherm.
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