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# RESERVOIR PARAMETER ESTIMATES AND WATER LEVEL PREDICTIONS FOR THE LAUGARNES LOW-TEMPERATURE SYSTEM, SW-ICELAND, BY SIMPLE ANALYTICAL AND LUMPED PARAMETER MODELS

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## ABSTRACT

The Laugarnes geothermal field is located near the centre of Reykjavík, SW-Iceland. It has been utilized since 1928. Currently, there are 12 production wells, producing geothermal fluids with an average temperature of 130°C and average total production rates of around 168 l/s. Monthly measured water level data exist from 1962 and indicate the reservoir's response to long-term production. In this paper, the data were analysed using a simple analytical method and the lumped parameter method. The results of the study indicate that the Laugarnes geothermal field is an open system with a combination of confined and free surface effects. The permeability of the Laugarnes geothermal system is estimated to be around 11 mD, and the area of the reservoir is between 21 and 940 km$^2$. The storativity is between $8.59\times10^{-8}$ and $1.02\times10^{-5}$ s$^2$/m$^2$. Both methods were used to predict water levels within the reservoir for 30 years into the future. The model's prediction of the reservoir's response, after 30 years of producing at a rate of 168 l/s, indicates a water level of between -51.10 and -32.60 m a.s.l. A comparison of the simple analytical method and the lumped parameter method highlights the different advantages of each method.

## 1. INTRODUCTION

Geothermal energy stems from the Earth's outward heat-flux, which creates geothermal systems in the Earth's crust. In the majority of cases, people obtain the energy from groundwater. Human beings have used geothermal resources for bathing, washing clothes and cooking for hundreds of years. During the 20th century, geothermal science made great progress with the advancement of related disciplines and technology. Electricity was first generated from geothermal resources at Larderello, Italy in 1904. Geothermal energy has also been used directly for district heating, for heating swimming pools, greenhouses and for many other uses. Today, geothermal resources have been identified in some 90 countries, with systematic utilization in more than 70 countries (Fridleifsson, 2003). Geothermal utilization is expected to develop rapidly in the future due to the world energy crisis and environmental issues.

Geothermal science is a science of comprehensive disciplines including geology, geophysics, reservoir engineering, chemistry, drilling technology and environmental science. A geothermal reservoir is a porous and/or fractured formation where the geothermal water can be stored and transported. Reservoirs can differ in nature and characteristics and will respond differently to long-term production. In the field of reservoir engineering, mathematical models are used to estimate the character and properties of the reservoir in order to (1) obtain information on reservoir properties and conditions, (2) predict reservoir response to future exploitation and estimate its potential and (3) aid in overall management of the resource. The goal of the modelling is to control and manage the reservoir in order to utilize the geothermal resources as efficiently as possible.

Reservoir modelling is a necessary method in geothermal resource development and management. Geothermal reservoir models can be classified as either static or dynamic (Table 1).

TABLE 1: Types of commonly used to geothermal reservoirs models

| Static model | Dynamic model |
|---|---|
| Volumetric method | Simple analytical models<br>Lumped parameter models<br>Detailed numerical models |

The volumetric method is typically used in the initial stages of geothermal reservoir development because it requires a minimal amount of data. As more data are collected from the reservoir, more robust dynamic models can be used for simulating long-term utilization. Detailed numerical modelling is the most powerful tool used to solve the problems of reservoir development. It is widely used in geothermal systems and can accurately simulate complicated geological properties, especially in high-temperature fields. Simple modelling, in which the geological information and properties of a geothermal system are greatly simplified, provides a more cost-effective and time-saving option than detailed numerical modelling.

Generally, people only have indirect data such as water level measurements and production flow rates from long-term utilization. This paper discusses reservoir parameters and water level predictions for the Laugarnes low-temperature field in SW-Iceland by using the simple analytical and lumped parameter methods.

## 2. THE LAUGARNES GEOTHERMAL FIELD, SW-ICELAND

The Laugarnes geothermal field is one of four low-temperature geothermal fields in the Reykjavík area in SW-Iceland, the others being the Ellidaár, Reykir, and Reykjahlíd fields (Figure 1). The Laugarnes low-temperature field is located near the centre of Reykjavík city. Exploitation of the Laugarnes field was initiated in 1928 by the Municipal District Heating Service of Reykjavík. Therefore, this field has been in production for more than 80 years. The temperature of the geothermal water produced from the field is around 130°C, and is mainly used for district heating but also for heating swimming pools, snow melting, etc.

### 2.1 Geological and hydrogeological background

### 2.1.1 Geological background

Iceland is a volcanic island due to its location at the boundary of two continental plates, the Eurasian Plate to the east and the North American Plate to the west. This divergent plate boundary creates a rift zone that crosses the island. This rift zone is very geologically active and there have been many volcanic eruptions along it in recent years. High-temperature geothermal systems are located within this active rift zone, and low-temperature fields occur on the edges of the zone. The Laugarnes geothermal system is a low-temperature field which lies on the western edge of the rift zone.

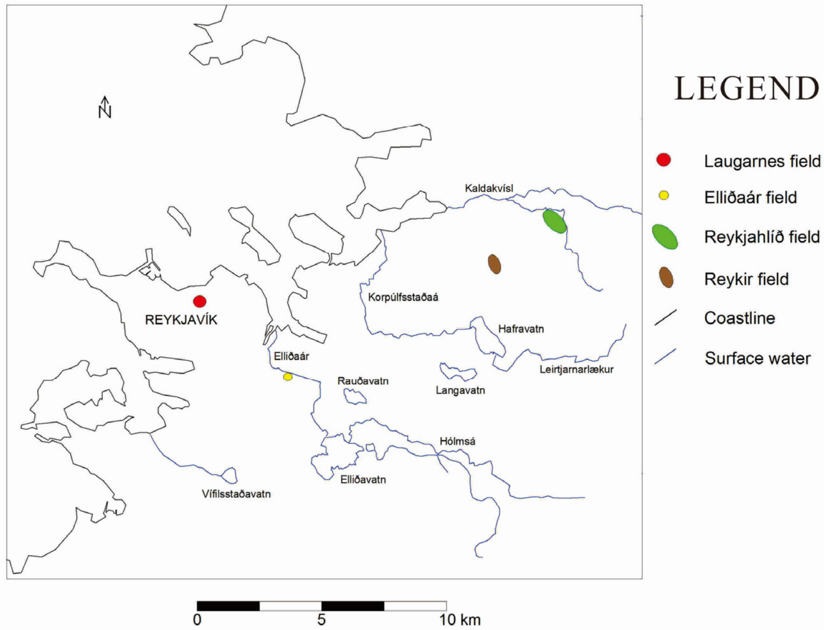

FIGURE 1: An overview of low-temperature fields in Reykjavík and vicinity (Myer and Hrafnkelsson, 2010)

The Reykjavík area is located near the southern end of the Tertiary plateau basalt series of west Iceland, bounded to the east and south by the Reykjanes quaternary volcanics (Thorsteinsson and Elíasson, 1970). The Laugarnes geothermal field is located within the city of Reykjavík. At the surface there are 30-60 m of thick coarse-grained olivian basalts with interglacial sediments towards the bottom. Underneath the sediments, basalt flows alternate with pyroclastics and sediments which are relatively thick. Many of the flow series exhibit pillow structures. Below 1250 m depth the pillow structures are no longer evident. The Tertiary strata in the Laugarnes area appear to dip 3 to 12 degrees towards the southeast.

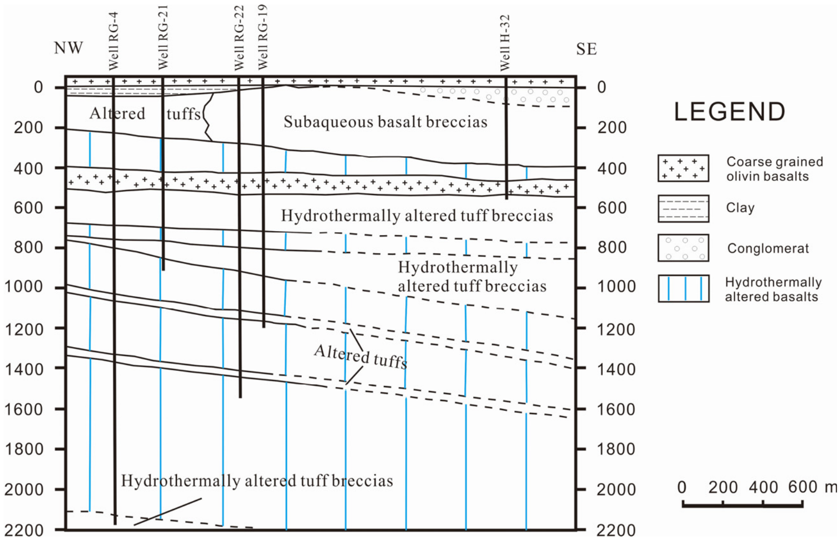

FIGURE 2: A NW-SE geologic cross-section through the Laugarnes geothermal system

Figure 2 gives a schematic NW-SE cross-section through the Laugarnes geothermal field. There are 5 geothermal wells in the cross-section. Well log data from the geothermal wells reveal the following stratigraphy:

0-300 m, mainly subaqueous basalt breccias and altered tuffaceous sediments;
300-400 m, altered basalts;
400-700 m, upper part is conglomerate, underneath are subaqueous basalt breccias;
below 700 m, mainly altered basalts with some breccias and small altered tuff layers.

The geological structure in this area is very complicated. It is believed to be associated with the intersection of SW-NE trending faults and fractures and the caldera rim of an extinct central volcano (Gunnlaugsson et al., 2000).

### 2.1.2 Hydrogeology

Production from the Laugarnes geothermal field occurs mainly below 700 m depth from basaltic lava formations. The observed water level in well RG-7 is about 20 m b.s.l. and the average production from the well field is 168 l/s. Studies show that the centre of the field has good hydraulic connection with the outer edges of the field from recharge through the rock fractures. The field's recharge zone was found by deuterium analysis studies (Árnason, 1977). According to the Árnason report, the Langjökull area to the northeast supplies the main recharge for the Laugarnes geothermal field. According to previous research and geochemical analysis, the geothermal water is supplied by three main reservoirs: reservoir A contains water between 110-120°C and extends from 250 to 650 m depth; reservoir B contains water around 135°C and extends from 730 to 1250 m depth; and reservoir C contains water around 146°C and extends below 2150 m depth (Thorsteinsson and Elíasson, 1970). Tuffaceous formations and sediments act as aquicludes between the reservoirs while scoriaceous and fractured contacts between individual lava flows have relatively high permeability. Because each lava flow thins out between overlying and underlying flows, the permeable zones within each reservoir are not continuous but may merge with those of adjacent flows. The estimated percentages of the total withdrawal of water are 18% from reservoir A, 80% from reservoir B and 2% from reservoir C. This indicates that reservoir B is the main geothermal reservoir.

Precipitation and surface water have little effect on the Laugarnes reservoir; no change in the temperature of the produced geothermal water has been observed. The surface thermal gradients in shallow wells in the Reykjavík area indicate transport of the geothermal water from the deeper part of the reservoir to the shallow part. The Laugarnes field is abnormal in that it has very high surface gradients of around 400°C/km (Tómasson et al., 1975). Thermal gradients in the areas surrounding Laugarnes are much lower. This implies that some faulted structures exist at Laugarnes which can transmit the thermal water and heat from deeper parts of the reservoir to the surface.

From the beginning of deep drilling in the 1960s, water levels and production rates have been measured periodically from many observation wells within the field. Figure 3 shows the water level data from geothermal well RG-7 since 1967 and production data from 1962. The fluctuation of the water levels reflects variations in pressure heads with variation in the pumping rate from the field. The average water level shows a slight drawdown from long-term production.

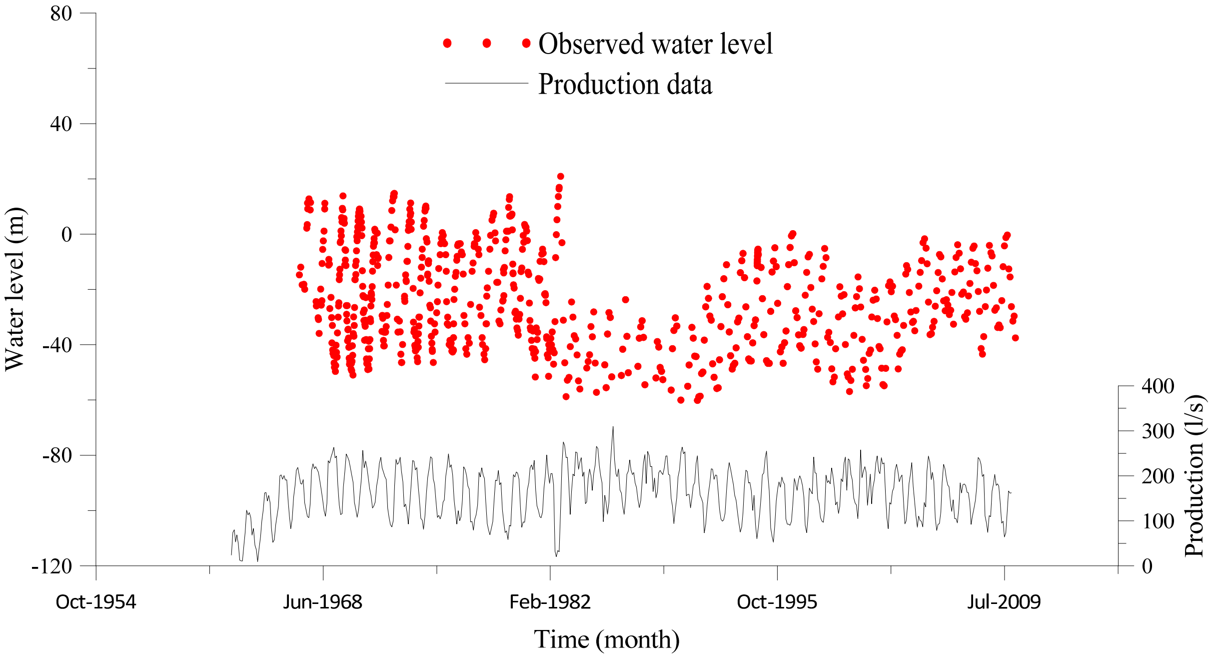

FIGURE 3: Production history and water level data from well RG-7 in the Laugarnes geothermal field

## 2.2 Production history and utilization

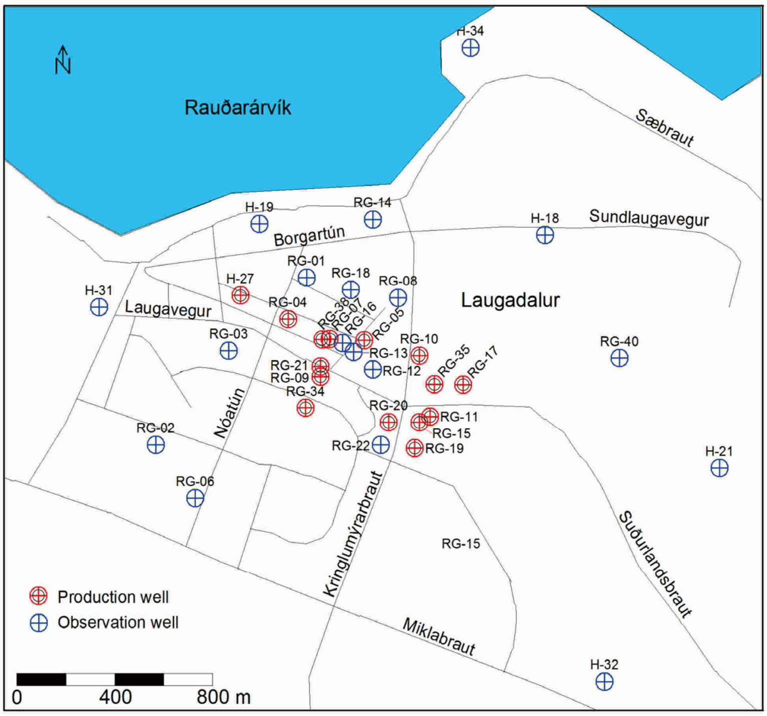

FIGURE 4: Location of geothermal wells in the Laugarnes geothermal field (Myer and Hrafnkelsson, 2010)

The Laugarnes geothermal field is one of six major geothermal fields exploited by the Municipal District Heating Service of Reykjavík. Others are the Ellidaár, Reykir, Reykjahlíd, Nesjavellir, and Hellisheidi fields, the last two being high-temperature fields. Between the years 1928 and 1930, 14 small diameter wells were drilled in the Laugarnes area near the Thvottalaugar hot spring in Laugadalur (Figure 4). The deepest well extended to a depth of 246 m. The total flow rates were 15-20 l/s with a produced temperature of approximately 95°C.

With improvements in drilling technology and the growing demand for heat energy, large-scale development began in 1958 in the Laugarnes geothermal field. Currently, there are more than 50 geothermal wells producing from the field. The deepest well (3085 meters) was drilled in order to explore possible deeper reservoirs. The average temperature of the produced water is 130°C.

Not all of the geothermal wells are connected with the district heating system; only the highest producing wells are used. Currently there are 10 wells in use (Table 2). The average total production was 168 l/s from 1963 to 2008. The data which were used for the purpose of this report were taken from well RG-7 and date from 1967 to 2010 (Figure 3). Also used were the average monthly production rates from 1962 to 2010 for the whole geothermal field (12 wells in all). Figure 3 shows that the water level in well RG-7 is affected by production wells. Drawdown increased with increased production rates from 1963 to 1990. The Laugarnes field produced 5.17 Gl of water in 2008, 7.6% of the total amount used in the Reykjavík area (Table 3).

TABLE 2: Information on production wells in the Laugarnes geothermal field for the year 2008 (Ívarsson, 2009)

| **Well no.** | **Year drilled** | **Depth (m)** | **Casing depth (m)** | **Temperature (°C)** | **Production (Gl)** |
|---|---|---|---|---|---|
| RG-5 | 1959 | 741 | 68 | 129.1 | 1.57 |
| RG-9 | 1959 | 860 | 350 | 124.5 | 0.19 |
| RG-10 | 1959 | 1309 | 92 | 132.1 | 0.42 |
| RG-11 | 1962 | 828 | 112 | 129.7 | 0.58 |
| RG-15 | 1962 | 1014 | 91 | 122.2 | 0.19 |
| RG-17 | 1963 | 634 | 93 | 121.1 | 0.11 |
| RG-19 | 1963 | 1239 | 82 | 127.6 | 0.76 |
| RG-20 | 1963 | 764 | 87 | 124.5 | 1.01 |
| RG-35 | 1979 | 2857 | 276 | 126.0 | 0.09 |
| RG-38 | 1982 | 1488 | 325 | 128 | 0.42 |

TABLE 3: Yearly production from the Laugarnes field from 1963 to 2008 (Ívarsson, 2009)

| Year | Production (Gl) | Year | Production (Gl) | Year | Production (Gl) | Year | Production (Gl) |
|---|---|---|---|---|---|---|---|
| 1963 | 1.92 | 1975 | 5.04 | 1987 | 5.79 | 1999 | 5.49 |
| 1964 | 2.65 | 1976 | 5.18 | 1988 | 6.46 | 2000 | 5.65 |
| 1965 | 3.77 | 1977 | 4.70 | 1989 | 5.81 | 2001 | 5.28 |
| 1966 | 5.14 | 1978 | 4.45 | 1990 | 6.07 | 2002 | 5.50 |
| 1967 | 5.38 | 1979 | 4.18 | 1991 | 5.26 | 2003 | 5.51 |
| 1968 | 5.88 | 1980 | 4.96 | 1992 | 4.95 | 2004 | 4.32 |
| 1969 | 6.34 | 1981 | 5.33 | 1993 | 4.70 | 2005 | 5.06 |
| 1970 | 5.57 | 1982 | 4.35 | 1994 | 4.73 | 2006 | 4.75 |
| 1971 | 5.85 | 1983 | 6.72 | 1995 | 4.83 | 2007 | 4.68 |
| 1972 | 5.20 | 1984 | 6.28 | 1996 | 4.46 | 2008 | 5.17 |
| 1973 | 5.69 | 1985 | 6.18 | 1997 | 4.95 | | |
| 1974 | 5.09 | 1986 | 5.96 | 1998 | 5.23 | Total | 235.49 |

## 3. THEORETICAL BACKGROUND AND METHODOLOGY

### 3.1 Simple analytical model

A simple analytical model was applied to a single phase fluid in a control volume with leakage and a free surface effect. An illustration (Figure 5) explains the setup for the simple analytical model, including leakage through an aquitard and free surface storage effects. In this model, it was assumed that the fluid is incompressible. Flow is governed by Darcy's law, which can be written in its simplest form as:

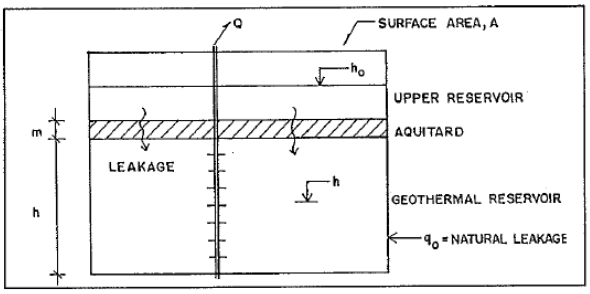

FIGURE 5: A simple analytical model of a geothermal system with leakage and a free surface (Vatnaskil Consulting Engineers, 1991)

$$V = -K \cdot \text{grad } h \tag{1}$$

where V = The Darcy velocity (m/s);
K = Hydraulic conductivity tensor (m/s); and
h = Reservoir pressure head (m).

The hydraulic conductivity, K, has dimensions of velocity. It is dependent on the viscosity and density of the geothermal fluid and the geometric properties of pore spaces in the rock matrix. If the coordinate system is aligned with the principal axes of anisotropy, the hydraulic conductivity is defined in two directions, $k_x$ and $k_y$. Transmissivity is, therefore, defined as:

$$T_x = k_x \cdot b \tag{2}$$

$$T_y = k_y \cdot b \tag{3}$$

where $T_x$ = Transmissivity in x direction ($m^2/s$);
$T_y$ = Transmissivity in y direction ($m^2/s$); and
b = Reservoir thickness (m).

The storage coefficient S is defined by the following equation:

$$S = \rho g \varphi (\frac{\gamma}{\varphi} + \beta) b \tag{4}$$

where $S$ = Storage coefficient (-);
$\rho$ = Density of geothermal water (kg/m$^3$);
$g$ = Acceleration of gravity (m/s$^2$);
$\varphi$ = Porosity (-);
$\gamma$ = Rock compressibility (Pa$^{-1}$); and
$\beta$ = Water compressibility (Pa$^{-1}$).

Based on the control volume in Figure 5, a lumped version of the equation of continuity becomes:

$$AS\frac{dh}{dt} = Q + \frac{k}{m}(h_0 - h)A \tag{5}$$

where $A$ = Reservoir surface area (m$^2$);
$S$ = Storage coefficient of geothermal reservoir (-);
$m$ = Thickness of aquitard (m);
$Q$ = Pumping rate (m$^3$/s) (negative value);
$k$ = Hydraulic conductivity (m/s);
$h_0$ = Potential in upper layers (m); and
$h$ = Potential in geothermal aquifer (m).

For the free surface a lumped equation of continuity is:

$$\varphi\frac{dh_0}{dt} = \frac{k}{m}(h_0 - h) \tag{6}$$

If we solve for the water level drawdown ($h_0$-h) in Equation 5 and insert it into Equation 6, we get:

$$AS\frac{dh}{dt} + A\frac{\varphi}{K_f}\int_0^t \frac{dh}{dt} e^{-(t-\tau)/K_f} d\tau = Q \tag{7}$$

The solution to Equation 7 is given by:

$$h_i - h = \frac{1}{A(\varphi + S)}\int_0^t Q(\tau)d\tau + \frac{\varphi}{SA(\varphi + S)}\int_0^t Q(\tau)e^{-(t-\tau)(\frac{1}{K_c}+\frac{1}{K_f})}d\tau \tag{8}$$

where $h_i$ = Initial reservoir water level head (m);
$h$ = Dynamic groundwater level (m);
$t$ = Time (s);
$K_c$ = Flow constant (s); and
$K_f$ = Time constant for free surface (s).

$K_c$ and $K_f$ are the flow constant and time constant for free surface, respectively, and are defined as:

$$K_c = \frac{mS}{K} \tag{9}$$

$$K_f = \frac{\varphi m}{K} \tag{10}$$

For further analysis, we can define the water level drawdown as $s = h_0 - h$. Equation 5 then becomes:

$$\frac{ds}{dt} + \frac{1}{k}s = \frac{Q'}{AS} \tag{11}$$

Where Q' is the net production (pumping and natural recharge). Equation 11 can be solved by multiplying through with $e^{t/k}$ as follows:

$$s = \int_0^t \frac{Q'(\tau)}{AS} e^{-(t-\tau)/k} d\tau \tag{12}$$

An approximate solution to Equation 12 is given by:

$$s \cong \frac{(Q_0 - q_0)}{AS}(1 - e^{-t/k}) + \frac{qk}{AS(1 + k^2\omega^2)^{1/2}} \sin\omega(t + \theta) \tag{13}$$

where $Q_0$ = Average pumping rate ($m^3/s$);
$q_0$ = Natural recharge ($m^3/s$);
$q$ = Pumping rate amplitude ($m^3/s$);
$\omega$ = The period of production (s ); and
$\theta$ = Time phase shift (s).

and $tg\omega\theta = \omega k$. The amplitude of the pressure head variations is described by:

$$a = \frac{qk}{AS(1 + k^2\omega^2)^{1/2}} \tag{14}$$

where $a$ = Amplitude (m).

For the case, when $\omega k << 1$, then:

$$a = \frac{q}{A(k/m)} \tag{15}$$

which is independent of the storage in the reservoir but depends upon the thickness and permeability of the aquitard. The phase difference $\theta$ is zero.

For the case $\omega k >> 1$, Equation 14 is given by:

$$a = \frac{q}{AS\omega} \tag{16}$$

In this case, the amplitude depends on the reservoir storage and the phase difference $\theta$ is now equal to 1/4 of the period.

## 3.2 Lumped parameter model

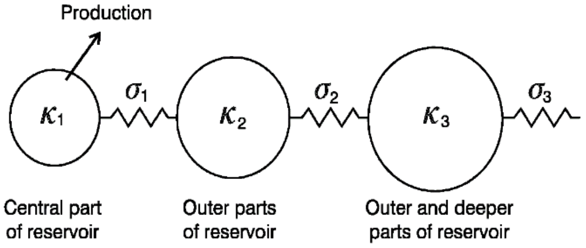

FIGURE 6: A general lumped parameter model used to simulate water level or pressure changes in geothermal systems (Axelsson, et al., 2005)

General lumped models also belong in the category of simple models. In this paper, the LUMPFIT program is mainly used for the simulations. It can automatically calculate the water level and fit the observed data by using a non-linear iterative least-squares technique. The theoretical basis of LUMPFIT was presented by Axelsson (1985 and 1989). The basic structure of the model is shown in Figure 6. It consists of several tanks and flow resistors which represent different storage capacities of the geothermal system and the flow resistance in the reservoir. Every tank has a storage capacitance κ, which determines how the reservoir responds to a load of liquid mass with a pressure increase depending on the size of the system and the storage mechanism, defined as:

$$\kappa = \frac{m}{p} \tag{17}$$

where $\kappa$ = Storage capacitance (kg/Pa or $ms^2$);
$m$ = Liquid mass change (kg); and
$p$ = Pressure change (Pa).

The corresponding flow resistor $\sigma$ controls the property relationship between liquid mass and pressure, and is controlled by the permeability of the reservoir rock and the geometry of the flow in a system, defined as:

$$\sigma = \frac{\Delta q}{\Delta p} \tag{18}$$

where $\sigma$ = Conductance of flow resistor (kg/sPa or ms);
$\Delta q$ = Liquid mass flow (kg/s); and
$\Delta p$ = Pressure differential (Pa).

The first tank for this model (Figure 5) simulates the production from the geothermal system within the centre of the reservoir. Other tanks simulate the outer parts of the system which have some connection with the central part. The outer parts can supply recharge to the central part. Lumped models can be classified as open or closed systems. Open systems may be considered optimistic, such that there would be some equilibrium during long-term production resulting in stable water levels. Closed systems may be considered pessimistic in that there is no recharge into the system. Water levels continue to decline during long-term production. Therefore, if there is sustained recharge into the reservoir, the system is open; otherwise it is a closed system. Basic equations for $\kappa$ and $\sigma$ for n tanks are described as:

$$\kappa_i \frac{dp_i}{dt} = \sum_{k=1}^{n} q_{ik} - \sigma_i(p_i - p_0) \tag{19}$$

$$\sigma_{ik} = \frac{q_{ik}}{p_k - p_i} \tag{20}$$

The solution of pressure in LUMPFIT is (Axelsson and Arason, 1992):

$$p(t) = p_0 - \sum_{j=1}^{n} Q\frac{A_j}{L_j}(1 - e^{-L_j t}) \tag{21}$$

$$p(t) = p_0 - \sum_{j=1}^{n-1} Q\frac{AP_{0j}}{L_j}\left(1 - e^{-L_j t}\right) - QBt \tag{22}$$

Equation 21 applies to open systems. Equation 22 applies to closed systems. $A_j$, $L_j$ and B are functions of the model parameters $\kappa_j$ and $\sigma_j$. The relationship between pressure and water level is:

$$p(t) = \rho g h(t) \tag{23}$$

When geothermal water is pumped out of the reservoir, the reservoir will respond and pressure will decline. Monitoring of the reservoir is typically done by measuring production and pressure. These data can be used to simulate and calculate the model parameters $\kappa_j$ and $\sigma_j$. By using $\kappa_j$ and $\sigma_j$, the reservoir properties can be estimated.

## 4. RESULTS

Data used for simulations included water level data from January 1967 to March 2010 and production data from the entire Laugarnes field from December 1962 to December 2009. The Laugarnes geothermal field has been exploited since 1928 and the initial water level before production is not known. Therefore, the initial water level is treated as an unknown parameter in the simulations. A reasonable range of 0-70 m a.s.l. was used for the initial water level within a 10 m interval.

### 4.1 Simulation with the simple analytical model

The simple analytical model was used to solve Equation 8 to calculate the water level and find a best fit with measured data. The water level is calculated from 6 parameters: storage coefficient, hydraulic conductivity, thickness of aquitard, porosity, the size of the reservoir, and initial water level.

The aquitard is assumed to be 150 m thick, the porosity $\varphi$ is set as 0.15 and the hydraulic conductivity, k as $4\times 10^{-9}$ m/s. These are reasonable values considering the geological and hydrogeological conditions in the reservoir and taking published values into account. The least-square method was used to compare calculated and observed water levels. The least-square method was also used in the lumped parameter model and is calculated as follows:

$$W = \sum_{i=1}^{n} R_i^2 \tag{24}$$

$$R_i = y_i - f(x_i) \tag{25}$$

where $W$ = Sum of squared residuals;
$R_i$ = Differentials between calculated water level and observed water level;
$y_i$ = Observed water level; and
$f(x_i)$ = Calculated water level.

First, we set the value of the initial water level and then, by using visual comparison and the least-square method, we find the best-fit parameters for the geothermal reservoir. The results of the simulation indicate that an initial water level of 60 m a.s.l. gives the best-fit as shown in Table 4 and Figure 7.

TABLE 4: Best-fit parameters of the simple analytical model of the Laugarnes geothermal system

| | |
|---|---|
| Initial water level (m) | 60 |
| Storage coefficient | $1.70\times10^{-4}$ |
| Hydraulic conductivity (m/s) | $4\times10^{-9}$ |
| Thickness of aquitard (m) | 150 |
| Porosity | 0.15 |
| Area ($m^2$) | $8.3\times10^{7}$ |
| Sum of squared residuals ($m^2$) | 39800 |

The results of the simulation indicate that a hydraulic conductivity value of around $4\times10^{-9}$ m/s gives the best result. Neither the thickness of the aquitard nor the porosity had much effect on the results in this model as long as they were within a reasonable range. These estimated parameters from the simulations, including the initial water level of 60 m and an average production rate of 168 l/s, were then used to calculate the following time constants.

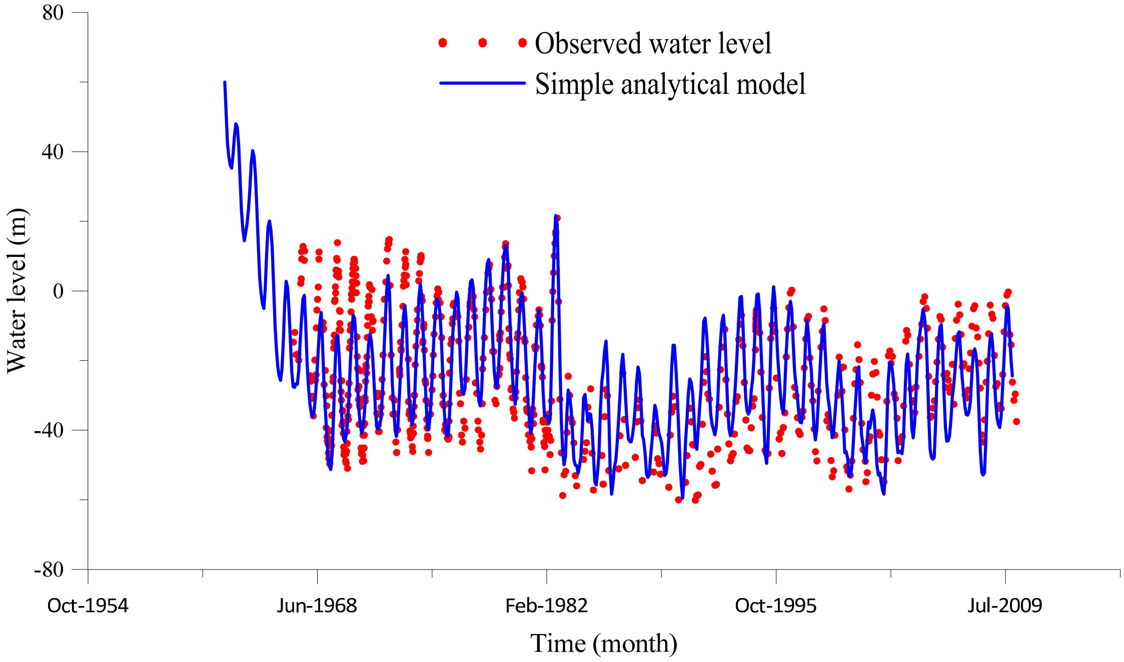

FIGURE 7: Comparison between the simulated (simple analytical model) and observed water level in the Laugarnes geothermal system

$$K_c = \frac{mS}{k} = \frac{150 \times 1.7 \times 10^{-4}}{4 \times 10^{-9}} = 6.38 \times 10^6 \text{ s} = 73.78 \text{ days}$$

$$K_f = \frac{\varphi m}{k} = \frac{0.15 \times 150}{4 \times 10^{-9}} = 5.62 \times 10^9 \text{ s} = 65104.17 \text{ days}$$

The calculated time constant $K_c$ for the flow is 73.78 days, and the free surface constant $K_f$ is about 65,100 days. The short term pressure response is then dominated by the elastic storage but the long term response is governed by the free surface effect. . From the observed data curve (Figure 7), the period of production is 1 year. For $K_c\omega << 1$, the amplitude is then given by:

$$a = \frac{q}{A(\frac{k}{m})} = \frac{0.05}{8.3 \times 10^7 \times (\frac{4 \times 10^{-9}}{150})} = 22.6 \text{ m}$$

For $K_f >> 1$, the amplitude for the free surface effect is:

$$a = \frac{q}{AS\omega} = \frac{0.05 \times 365 \times 86400}{8.3 \times 10^7 \times 1.7 \times 10^{-4} \times 2 \times 3.14} = 17.8 \text{ m}$$

The drawdown amplitude is controlled by the elastic time constant, but does not depend on the elastic storage itself. The long-term drawdown is actually the first part of Equation 8:

$$\frac{ds}{dt} = \frac{Q}{A(\varphi + S)} \tag{26}$$

The long-term drawdown assuming no free surface effect is:

$$\frac{ds}{dt} = \frac{Q}{AS} = 375 \text{ m/year}$$

and assuming no elastic storage:

$$\frac{ds}{dt} = \frac{Q}{A\varphi} = 0.43 \text{ m/year}$$

The results assuming no free surface effect are very different from the observed data. Assuming no elastic storage, the estimated average drawdown from 1963 to 2012 was 0.43 × 50 = 21.5 m. This result seems reasonable.

### 4.2 Simulation with a lumped parameter model

In the lumped parameter model, both a 2-tank closed and a 2-tank open tank model were used, with an estimated initial water level. The results were obtained by running the LUMPFIT program. The simulations indicated that a 70 m a.s.l. initial water level gives the best fit within a range of 0 ~ 70 m (Table 5).

TABLE 5: Main parameters of the closed and open lumped parameter models of the Laugarnes geothermal system, assuming a 70 m initial water level (using LUMPFIT)

| System | 2-tank closed model | 2-tank open model |
|---|---|---|
| Sum of squared residuals ($m^2$) | 41200 | 26300 |
| Coefficient of determination | 75.2% | 84.2% |
| Storage capacitance $\kappa_1$ ($ms^2$) | 1714.8 | 1703.4 |
| Storage capacitance $\kappa_2$ ($ms^2$) | $1.08\times10^7$ | $1.19\times10^6$ |
| Conductance $\sigma_1$ (ms) | $0.18\times10^{-3}$ | $0.23\times10^{-3}$ |
| Conductance $\sigma_2$ (ms) | - | $0.46\times10^{-3}$ |

The storativity depends on the storage mechanism. For the second tank, the outer part of the geothermal system is either confined liquid-dominated or free surface, or a combination of the two. Therefore, we have:

$$S_c = \rho_w(\varphi C_w + (1-\varphi)C_r) \tag{27}$$

$$S_f = \varphi/gh \tag{28}$$

where $S_c$ = Compressibility storativity ($s^2/m^2$);
$S_f$ = Free surface storativity ($s^2/m^2$);
$\rho_w$ = Density of geothermal water ($kg/m^3$);
$\varphi$ = Rock porosity;
$C_w$ = Fluid compressibility ($Pa^{-1}$);
$C_r$ = Rock compressibility ($Pa^{-1}$); and
$h$ = Reservoir thickness (m).

We can estimate the principal properties and characteristics of the reservoir by assuming two-dimensional flow for the 2 tank model (Figure 8). Parameters $R_1$ and $R_2$ indicate the radius of tank 1 and tank 2, respectively, while $r_1$ and $r_2$ indicate the half radius of each of the two tanks described by the equations in Table 6.

The estimated storativities and radii of the two tanks can be used to calculate the permeability of the reservoir. The relationships between storage capacitance and storativity, flow conductance and permeability are described as:

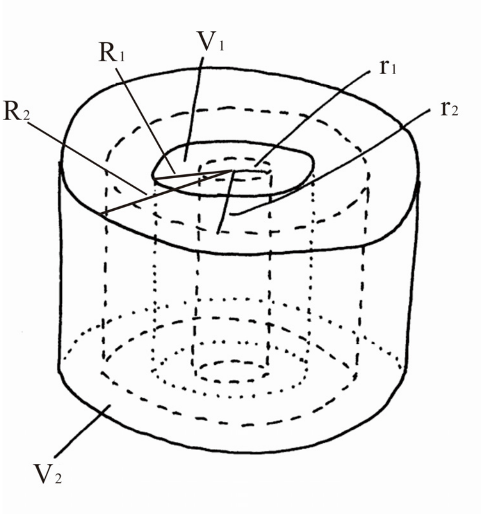

FIGURE 8: Two-tank closed and open lumped parameter models with two-dimensional flow

$$\kappa_1 = V_1 S \tag{29}$$

$$\kappa_2 = V_2 S \tag{30}$$

$$\sigma_1 = 2\pi hk/\ln\left(\frac{r_2}{r_1}\right)v \tag{31}$$

$$\sigma_2 = 2\pi hk/\ln\left(\frac{r_3}{r_2}\right)v \tag{32}$$

where $v$ = Kinematic viscosity of fluid ($m^2/s$).

The permeability can be deduced by:

$$k_i = \sigma_i \frac{\ln\left(\frac{r_{i+1}}{r_i}\right)v}{2\pi h} \tag{33}$$

The parameters are estimated by using the above equations. Table 7 shows the results. For the second tank, both compressibility storativity and free surface storativity were used to estimate the reservoir area.

TABLE 6: Equations for the half radius of each tank in a two-tank lumped parameter model assuming two-dimensional flow

| | |
|---|---|
| 2-tank closed model | $r_1 = \frac{R_1}{2}$ |
| | $r_2 = R_1 + \frac{R_2 - R_1}{2}$ |
| 2-tank open model | $r_1 = \frac{R_1}{2}$ |
| | $r_2 = R_1 + \frac{R_2 - R_1}{2}$ |
| | $r_3 = R_2 + \frac{R_2 - R_1}{2}$ |

TABLE 7: Estimated reservoir parameters of the Laugarnes geothermal system based on the two lumped parameter models

| **Model** | **2-tank closed model** | **2-tank open model** |
|---|---|---|
| Reservoir thickness (m) | 1500 | 1500 |
| Compressibility storativity ($s^2/m^2$) | $8.59\times10^{-8}$ | $8.59\times10^{-8}$ |
| Free surface storativity ($s^2/m^2$) | $1.02\times10^{-5}$ | $1.02\times10^{-5}$ |
| Volume of the first tank ($m^3$) | $2.00\times10^{10}$ | $1.98\times10^{10}$ |
| Volume of the second tank ($m^3$) | $1.26\times10^{13}$ | $1.39\times10^{12}$ |
| Volume for free surface ($m^3$) | $1.06\times10^{11}$ | $1.17\times10^{10}$ |
| Radius of the first tank (m) | 2058.4 | 2051.9 |
| Radius of the second tank (m) | 51800 | 17300 |
| Permeability between tanks (D) | 0.014 | 0.012 |
| Permeability with outer part (D) | - | 0.011 |
| Reservoir area ($m^2$) | $8.41\times10^7$~ $8.42\times10^9$ | $2.10\times10^7$ ~ $9.37\times10^8$ |

Comparing the parameters between closed and open models, the 2-tank open model gives a lower value for the volume, permeability and area than the 2-tank closed model. This is due to the fact that the open geothermal system has some hydraulic connection with the outer part of system, and thus receives more recharge through the formation fractures. The area is dependent on the storativity values. The storativity is between $8.59\times10^{-8}$ and $1.02\times10^{-5}$ $s^2/m^2$. If the reservoir is assumed to have a free surface, then it will be smaller. The permeability range is 0.011 to 0.014 D. From Table 5 it can be seen that the 2-tank open model has a better coefficient of determination than the 2-tank closed model, and the estimated parameters for the open model in Table 7 are also reasonable for the Laugarnes reservoir. It can be deduced from the LUMPFIT program that the Laugarnes geothermal field is an open system. Figure 9 shows a comparison between the water levels in the Laugarnes system simulated by the lumped parameter model and the observed water levels.

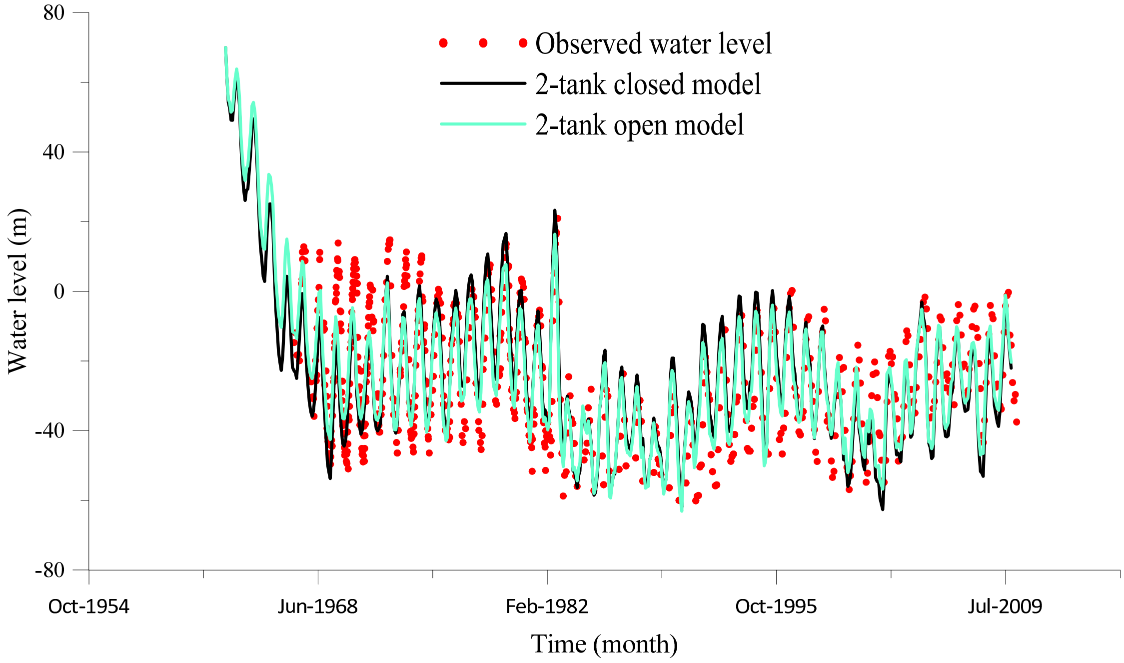

FIGURE 9: Comparison between the simulated (lumped parameter model) and the observed water levels in the Laugarnes geothermal system

### 4.3 Comparison between the two methods

Both the simple analytical model and the lumped parameter model can find the best-fit parameters for the geothermal reservoir provided reasonable physical constraints on the parameter values are applied. Figure 10 shows that the simulated water levels have some similarities, but also small differences due to different mechanisms within the models. The simple analytical model simulates a flow within a control volume with free surface effects. The calculated water level from the simple analytical model has a declining trend, as does the water level from the lumped parameter 2- tank closed model. The 2-tank open model, on the other hand, produces a stable water level.

The calculated reservoir area for both the simple analytical model and the 2-tank closed model with the free surface effect are both around $8.3\times10^7$ m$^2$. But in reality, this geothermal field is an open system, indicated by the fact there has been no change in the chemical composition or temperature within the reservoir, and the storativity is always affected by a combination of liquid-dominated and free surface effect. Therefore, the reservoir area calculated from the 2-tank open model ($2.10\times10^7 \sim 9.37\times10^8$ m$^2$) is a more accurate estimate. The estimated initial water level for both methods is 60-70 m a.s.l.

### 4.4 Future prediction

Two methods were used to simulate water levels in the reservoir for 30 years into the future, assuming the future production remains at the current average production, 168 l/s. Figure 10 shows the results from the two methods. The results for the simple analytical model and the 2-tank closed model are similar. The calculated water level shows continuous drawdown into the future. The final calculated water level from the simple analytical model is -48.87 m a.s.l., and from the 2-tank closed model is -

51.10 m a.s.l. The 2-tank open model has a relatively stable water level, with a final calculated level of -32.60 m a.s.l. Generally, the best estimate of the water level should be somewhere between the open and closed model curves (-51.10 to -32.60 m a.s.l.).

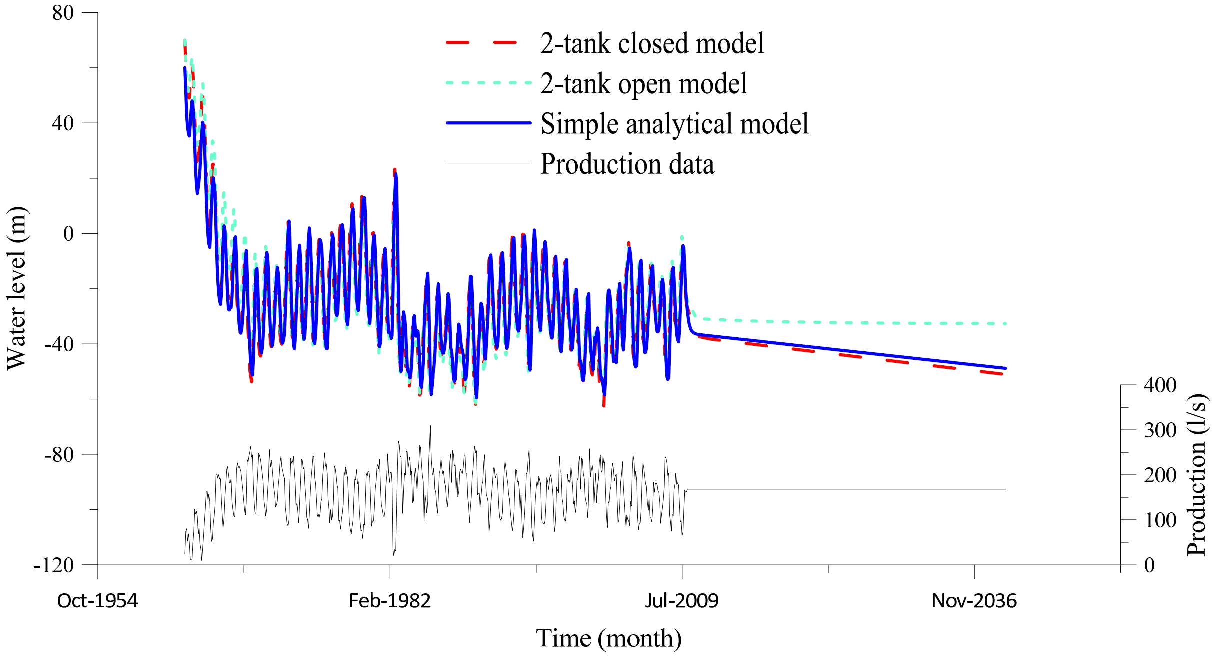

FIGURE 10: Predicted water level changes in the Laugarnes geothermal system for the next 30 years for a yearly average production of 168 l/s, calculated with the simple analytical model and open and closed lumped parameter models

## 5. DISCUSSION

From the above-mentioned simulations, it is found that both simple analytical modelling and lumped parameter modelling are powerful tools in reservoir engineering. The models require measurements of water levels in the reservoir and production data. Although they produce less accurate results than more detailed numerical models, these simple modelling techniques are less time-consuming and more cost effective. Used properly, they can be a useful tool for managing geothermal fields.

In this paper, the simple analytical method is based on Darcy's law. The model simulates a single-phase fluid within a free surface reservoir. In the final equation (Equation 8), there are 6 parameters which must be determined: storage coefficient S, hydraulic conductivity k, thickness of aquitard m, porosity φ, the size of reservoir A, and initial water level $h_i$. Estimation of these parameters requires a basic understanding of the geothermal system in question. Trends in the measured water levels can be used to estimate parameters. Experience indicates that the initial water level is related to the curve's height while the storage coefficient, hydraulic conductivity, and the area of the reservoir are related to the curve's shape. Neither the thickness of the aquitard nor the porosity have much effect on the curve, and should be defined in the final step of the modelling. For example, adjusting the hydraulic conductivity k by one order of magnitude would cause the calculated curve to shift up or down by a large amount. Another method is to use a program like SOLVER in Excel and allow it to solve for the best-fit parameters assuming some sensible physical constraints on the parameters.

The LUMPFIT program is a powerful code for simulating geothermal reservoirs. The calculated results are generally accurate, however sometimes some of the estimated parameters are unrealistic with regard to the geological or hydrogeological conditions. It is difficult to change the basic parameters directly in the programme. Comparisons indicate that simple analytical methods are more intuitive than lumped parameter methods.

The calculated area can be quite different depending on which method is used. Therefore, it is best to use different models, compare the results, and choose the most realistic values. In this paper, parameters like hydraulic conductivity were not compared because they were treated differently in the different models. The hydraulic conductivity in the simple analytical method represented mainly the aquitard's hydraulic conductivity, but in the lumped parameter method, it represented the hydraulic conductivity of the entire reservoir.

## 6. CONCLUSIONS

The main conclusions that can be drawn from this study are the following:

- The Laugarnes geothermal field is a low-temperature, open geothermal system. The reservoir receives free surface leakage and the water levels have shown slight drawdown during long-term utilization. The reservoir most likely receives recharge from a large area with free surface effect because there is little change in chemistry and temperature over its production history (Myer and Hrafnkelsson, 2010). Complicated geological structures and a fractured zone supply a good recharge channel.

- The properties of the reservoir were estimated using a lumped parameter model. The results indicate a reservoir size between $2.10\times10^7$ and $9.37\times10^8$ m$^2$ and it is probably closer to $2.10\times10^7$ m$^2$. The calculated permeability is around 0.011 mD. The calculated storativity is between $8.59\times10^{-8}$ and $1.02\times10^{-5}$ s$^2$/m$^2$. Using the simple analytical model, the calculated time constant is 73.78 days and the flow constant is about 65,100 days. The calculated flow constant plays an important role in long-term production. The calculated amplitude is 17.8 m. The average drawdown is around 0.43 m/year assuming the reservoir is a closed system without elastic storage.

- The model predictions of the reservoir's response after 30 years production at a rate of 168 l/s indicate a water level between -51.10 and -32.60 m a.s.l. The Laugarnes geothermal field has been exploited since 1928 and there has been more than 100 m of drawdown within the reservoir over that time. Although there are some indication that the reservoir is an open system reservoir, the monitoring system should be strengthened in order to follow future changes in reservoir pressure. Reducing production or initiating reinjection could be required if drawdown exceeds reasonable limits.

- The estimated reservoir area is $2.10\times10^7$ - $9.37\times10^8$ m$^2$. This corresponds to a circular area with 2.5-17 km radius. The Ellidaár geothermal field lies 3 km to the southeast of the Laugarnes field. Some hydraulic connection between the two fields is expected, as they are not completely separate systems. It can be deduced that there is one large, main Reykjavík low-temperature field which consists of several small reservoirs. There is still a need for chemical, geological and geophysical data, as well as modelling work in order to accurately define the entire Reykjavík reservoir.

- Simple models are cost efficient and adequate for the Laugarnes reservoir modelled in this study. In this paper, the simple analytical model was utilized and the LUMPFIT program was used for simulations. These methods provide a powerful way to simulate water level changes in geothermal reservoirs. In general, scientists should combine and compare the different models and then choose a reasonable result.

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