PROCEEDINGS, 50th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 10-12, 2025
SGP-TR-229

Simulation of Pressure Response in Geothermal Reservoirs by an Updated Lumped Parameter Method – Hjalteyri Case Study

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Keywords: Lumped parameter modeling, pressure changes, predictions, model reliability, Hjalteyri, Hrolleifsdalur, LUMPFIT, Lumpfit v3, Lumpfit++

ABSTRACT

Lumped parameter modeling of pressure response data has been applied to many low-temperature geothermal reservoirs in Iceland as well as worldwide. This method simulates the pressure response of a reservoir by using a small number (less than 10) of linearly connected, homogenous (or lumped) volumes. The method, therefore, requires very little computing time compared to more detailed numerical modeling. The method has proved to be very successful in predicting pressure changes and has been applied as a tool for resource assessment and management in production fields for more than four decades. The presently implemented method is limited to a single source of production and has a limited number of connections between reservoir volumes. Increasing hot water consumption in Iceland over the last decades has led to increased production from geothermal fields, and an increased number of wells per field. Hence, the increased complexity of reservoir geometry calls for the enhancement of the general lumped parameter method presented in 1989. We present the results of the updated method, using Hjalteyri in Eyjafjordur, N-Iceland, as a case study.

1. INTRODUCTION

Lumped parameter modeling is used in various geosciences. It refers to the concept of simplifying a physical model to make a model of main variables, where the geometry is often ignored, and variable physical parameters are lumped into simpler parameters. The response of the system can furthermore be described by analytical functions of the main variables. An overview of lumped parameter models in geophysics is given by Bodvarsson (1966). This includes for example magneto-telluric models where the variables are magnetic field intensity and electric field intensity, and the lumped parameters are resistivity and magnetic permeability, thermal models where the variables are temperature and heat flow, and the lumped parameters are heat conductivity and heat capacity. The best known lumped parameter models are used in electric circuit theory where the variables are voltage and current and the parameters are capacitors and resistors.

For hydrological systems, lumped models of pressure response primarily consider pressure and fluid flow as the main variables, while the key lumped parameters are storativity and hydraulic permeability. For hydrothermal systems, both lumped models of pressure response and temperature changes can be an important tool for modeling system response to the extraction of mass and heat from the system. Although advances in computing power have reduced interest in these models—due to the improved capabilities of complex numerical models—they remain an important tool for managing hydrological and hydrothermal systems, especially when data is limited. In such cases, constructing and calibrating complex models becomes difficult. Lumped parameter models can also be a time-saving alternative as well as acting as constraints for numerical models.

In this paper, we are looking at the advantages of utilizing a lumped parameter method developed by Axelsson (1985; 1989) to model pressure response in geothermal reservoirs. Furthermore, we will discuss the performance of two computer programs: (1) Lumpfit v3, based on codes developed in the 1980s (Axelsson, 1985, 1989; Axelsson and Arason, 1992; Gylfadóttir, 2014), and (2) the newly developed Lumpfit++ (Marteinsson et al., 2024), both of which implement the method. An overview of other lumped-parameter models for low-temperature geothermal systems is given by Sarak et al, (2005).

2. THE LUMPFIT METHOD

The mathematical model that the lumped parameter method is based on is described by Axelsson (1989). Lumped parameter models of geothermal reservoirs consist of a few tanks that are connected by conductors. This is analogous to an electrical circuit where several capacitors, the tanks, are connected by resistors. Each tank simulates the storage of different zones of a geothermal system, whereas the conductors represent the permeable pathways between these zones. An example of a basic lumped model of one tank connected to an infinite zone of recharge is presented in Figure 1a, and a more general lumped system is shown in Figure 1b.

A tank in a lumped model is characterized by its mass storage coefficient κ, defined as the ratio between the pressure, p, and the liquid mass in the tank, m, i.e. $\kappa = m/p$. A conductor between two tanks in a lumped model is characterized by its mass conductance σ, defined as the ratio between the mass flow rate in the conductor, q, and the pressure difference between the connected tanks, Δp, i.e. $\sigma = q/\Delta p$. The pressure (water level) in the tanks simulates the pressure in different parts of the reservoir, whereas production from the reservoir is simulated by the withdrawal of liquid mass from one or more of the tanks (Figure 1a).

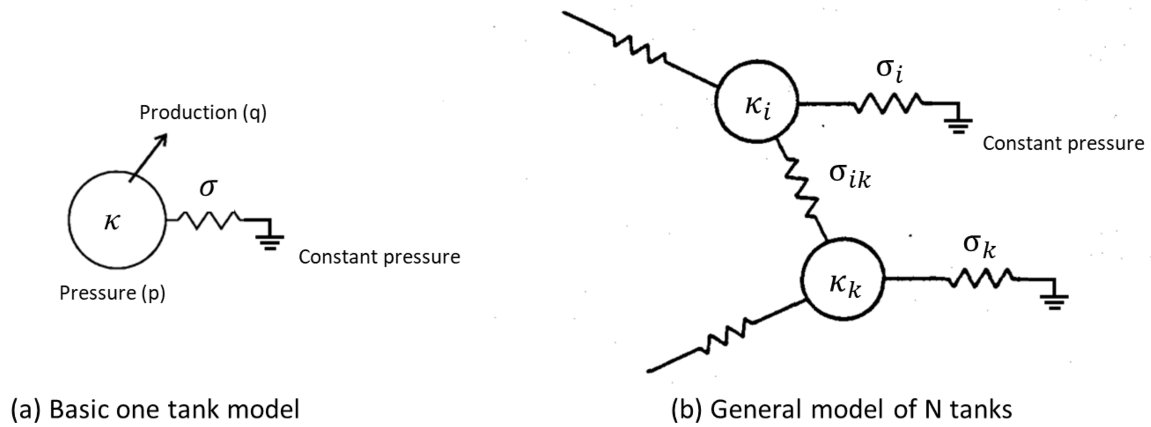


Figure 1: (a) A basic model of one tank connected to a constant pressure boundary and (b) a general model of N-tanks, that are interconnected as well as being connected to a constant pressure boundary. Based on drawings in Axelsson's original paper (Axelsson. 1989).

Let κ_i be the capacitance of tank i, such that the pressure in the tank changes when liquid mass m is added or removed like:

$$\Delta p_i = \frac{m}{\kappa_i} \tag{1}$$

Let σ_{ik} be the conductance between tanks i and k, such that:

$$q_{ik} = \sigma_{ik}(p_k - p_i) \tag{2}$$

describes the liquid mass per unit time that is transferred due to the pressure difference between the two tanks. It assumed that $\sigma_{ik} = \sigma_{ki}$. We also define σ_i to be the conductance between tank i and an infinitely large (recharge) tank (Figure 1b).

Using the law of the conservation of mass we can show that the pressure in tank i is:

$$\kappa_i \frac{dp_i}{dt} = \sum_{k=1}^{N} q_{ik} - \sigma_i p_i + f_i \tag{3}$$

where f_i signifies the mass sink/sources in the tank. Using equation (2) we can rewrite this as:

$$\kappa_i \frac{dp_i}{dt} = \sum_{k=1}^{N} \sigma_{ik}(p_k - p_i) - \sigma_i p_i + f_i \tag{4}$$

Since such an equation exists for each tank, the lumped system can be described using the differential equation:

$$\boldsymbol{K}\frac{d\mathbf{p}}{dt} + \boldsymbol{A}\mathbf{p} = \mathbf{f} \tag{5}$$

where $\mathbf{p}$ and $\mathbf{f}$ are vectors describing the pressure and the sinks/sources in each tank, respectively, and $\boldsymbol{K}$ and $\boldsymbol{A}$ are known as the capacitance and the conductance matrices, respectively. Since we would like to calculate the pressure in each tank as a function of time, we need to solve equation (5). The mathematical solution behind the Lumpfit-method is elaborated on in Axelsson's original paper from 1989 (Axelsson, 1989).

2.1 Linear (ladder) model

A computer program for solving a system of linearly connected tanks, shown in Figure 2 was developed by Axelsson and Arason (1992) based on a preliminary original version from 1985 (Axelsson, 1985). This program was named LUMFIT Version 3.1. The program was developed at the National Energy Authority of Iceland (Orkustofnun) and has been maintained and updated at Iceland GeoSurvey (ÍSOR) since it was founded in 2003. In 2014 it got a facelift when it was implemented in Python and published with a graphical user interface (Gylfadóttir et al., 2014). The present version of the program is referred to as Lumfit v3 (or simply Lumpfit).

The set of equations for the liner model is given in Axelsson and Arason (1992), being a special case of the more general model from the 1980's. The method and program have proven to be highly useful, with their predictive reliability demonstrated in numerous low-temperature fields in Iceland and worldwide, see e.g. Axelsson and Gunnlaugsson (2000), Axelsson et al. (2005a) and Axelsson et al. (2015).

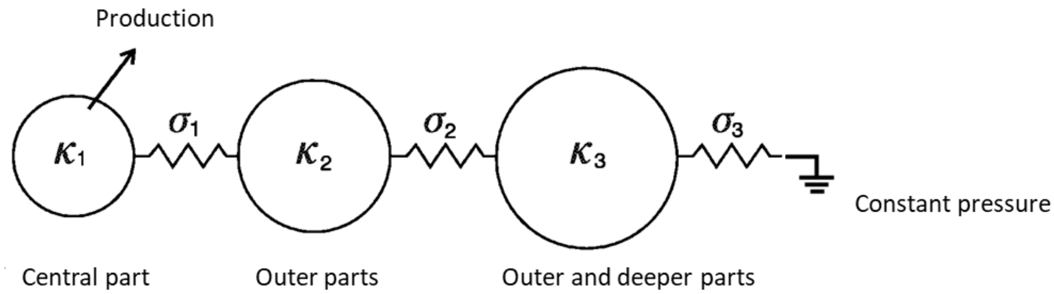


Figure 2: A linear open three-tank model based on drawings in Axelsson's original paper (Axelsson, 1989). A closed version of the model is missing the third conductor with a connection to a constant pressure boundary.

A recent example from the Hrolleifsdalur geothermal system in North Iceland is shown in Figure 3. In Hrolleifsdalur there are two production wells, SK-28 and SK-32, and during most of the production period, water level changes have been monitored in both wells. The water level data in SK-28, and total production from both wells, were fitted with the Lumpfit v3 program in 2019. The best fit was obtained with an open 2-tank model on the one hand and a closed 2-tank model on the other. The open and closed versions of the 2-tank model represent optimistic and pessimistic future water level predictions, respectively. In 2023, these models were revisited, and water level predictions—obtained by running the models with actual total production data—were compared with the observed water level (Tulinius and Thorgilsson, 2023). The measured water level falls between the two predictions, demonstrating the reliability of the models.

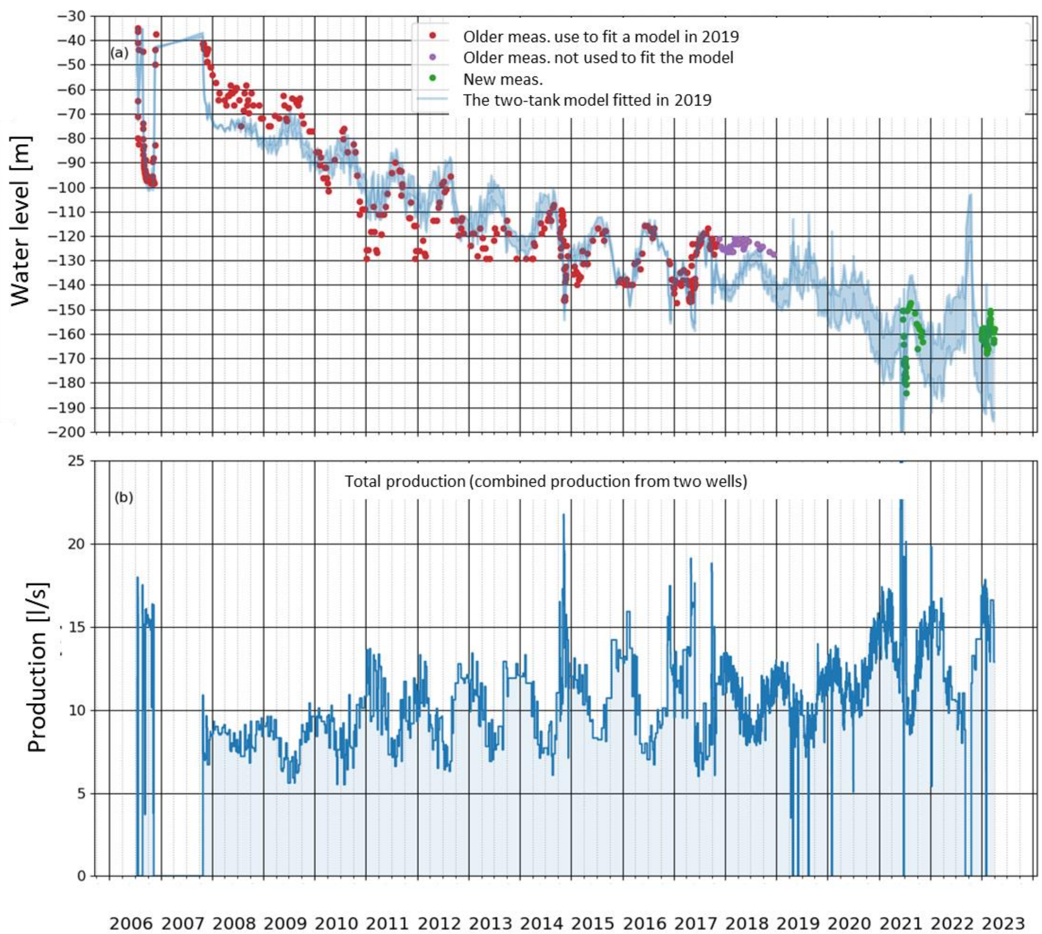


Figure 3: (a) Comparison of observed and calculated water level in the Hrolleifsdalur-reservoir in N-Iceland. The calculated values were obtained using a closed and open 2-tank model, representing pessimistic and optimistic predictions, respectively. (b) Total production from the reservoir. Two 2-tank linear models were fitted to water level measurements (red dots) in 2019, one open model and another closed model. The predicted water level by the two models is shown after 2019, the measurements falling between the two predictions. From Tulinius and Thorgilsson (2023).

The reliability of the Lumpfit models has been demonstrated in various other successful field cases. A drawback is that, based on the available production data, a single water level data-series must be chosen to represent changes in the system, and net production must be estimated. Since production and re-injection can come from multiple sources (wells) at different times, this approach can in some cases be overly simplistic.

2.2 General model

A computer program for solving the general N-tank system with production from more than one tank was developed at ÍSOR in 2024 (Marteinsson et al., 2024). The solution method is based on solving the system described by Axelsson (1989). The program was developed in Python and was published with a graphical user interface. It uses a least square method to fit the modeled production and pressure to the observed data. This program is called Lumpfit++.

The main motivation for developing Lumpfit++ is the increase in production from geothermal fields due to increased hot water consumption in the last decades. To meet the demands, more wells are now utilized for production within each field, compared to the 1980s and 1990s when the Lumpfit program was developed based on a simple linearized model with production from a single tank. The newly developed program allows the user to model simultaneously water levels in each production well as well as in additional observation wells.

3. HJALTEYRI CASE STUDY

Hjalteyri is located on the W-shore of Eyjafjordur in North Iceland. It is one of many known low-temperature geothermal systems around the fjord (Figure 4). There are no thermal manifestations on the surface and the system is one of the so-called hidden geothermal systems in Iceland that have been discovered in recent decades (Gautason et al., 2005; Axelsson et al., 2005a). The system was discovered when a high temperature gradient (100-110°C/km) was noted in shallow water wells (Gautason et al., 2005). Following a thorough shallow temperature gradient well survey, the first production well, HJ-19, was drilled in the center of the thermal anomaly in 2002.

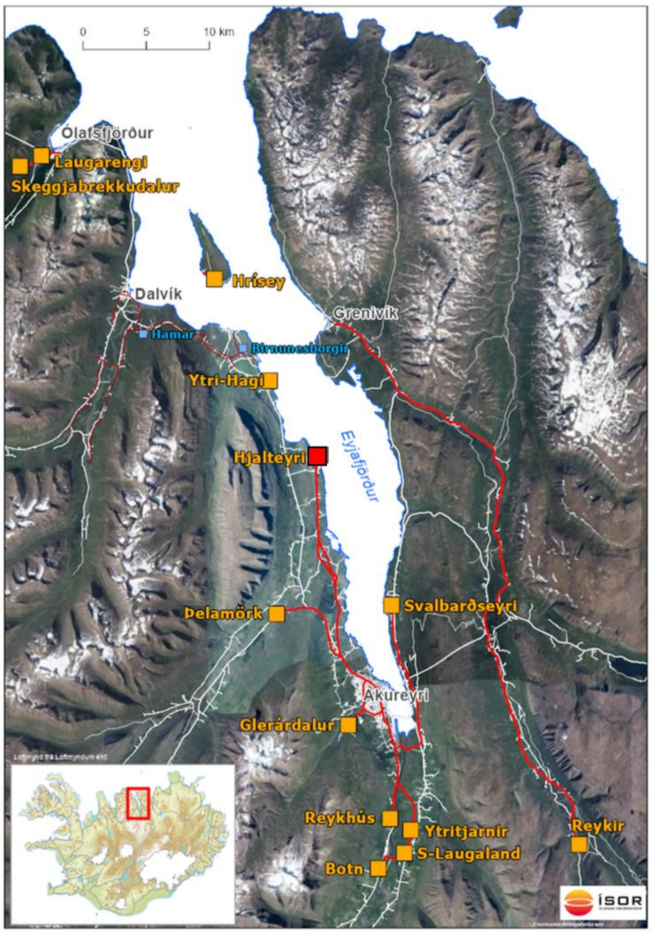


Figure 4: The Hjalteyri geothermal system is located in central north Iceland and is one of many known geothermal systems around Eyjafjördur fjord. The town of Akureyri, the largest town outside the Greater Reykjavik area, is shown in the figure.

The system is extremely permeable, and the first modeling results indicated that the field is capable of yielding up to 200 L/s of 90°C hot water with limited drawdown (Gautason et al., 2005). This has later been confirmed by more recent modeling (Egilsson et al, 2021; Egilsson, 2024). Seismic activity detected in the area could be responsible for the high permeability within the system. Seismic events have been detected beneath the system, outlining an underlying structure trending NNW (Axelsson et al., 2024). This structure coincides with the direction of other fields located on the west shore of Eyjafjordur. The proposed structure could be responsible for the intensity of the geothermal activity by enhancing the natural convection of fluid and heat transfer from depth (Halldorsdottir et al., 2023).

3.1 Production History

There are 3 production wells located in the center of the well field (Figure 5), HJ-19, HJ-20, and HJ-21. Together with the deepest exploration well, HJ-18, they provide valuable information about the system. They are located within what is believed to be the center of the geothermal up-flow, based on the geothermal gradient and results from the drilling of the four wells. The production history of the field is shown in Figure 6. The pressure response of the four wells is shown together with the production in each of the three production wells. At present there is no re-injection into the system. The depth of the three production wells varies between 1298 and 1515 m while the depth of the monitoring well, HJ-18, is 463 m.

A comparison of the observed water level in the four wells reveals that the pressure in the monitoring well, HJ-18, reflects quite well the production response of the production wells (Figure 6). The total production from the three wells is shown in Figure 7, illustrating the gradual increase in production over time. These wells are connected to Nordurorka's district heating facilities, supplying Akureyri and neighboring municipalities. The growing demand for hot water in the area has been met by increasing the production from the Hjalteyri-reservoir.

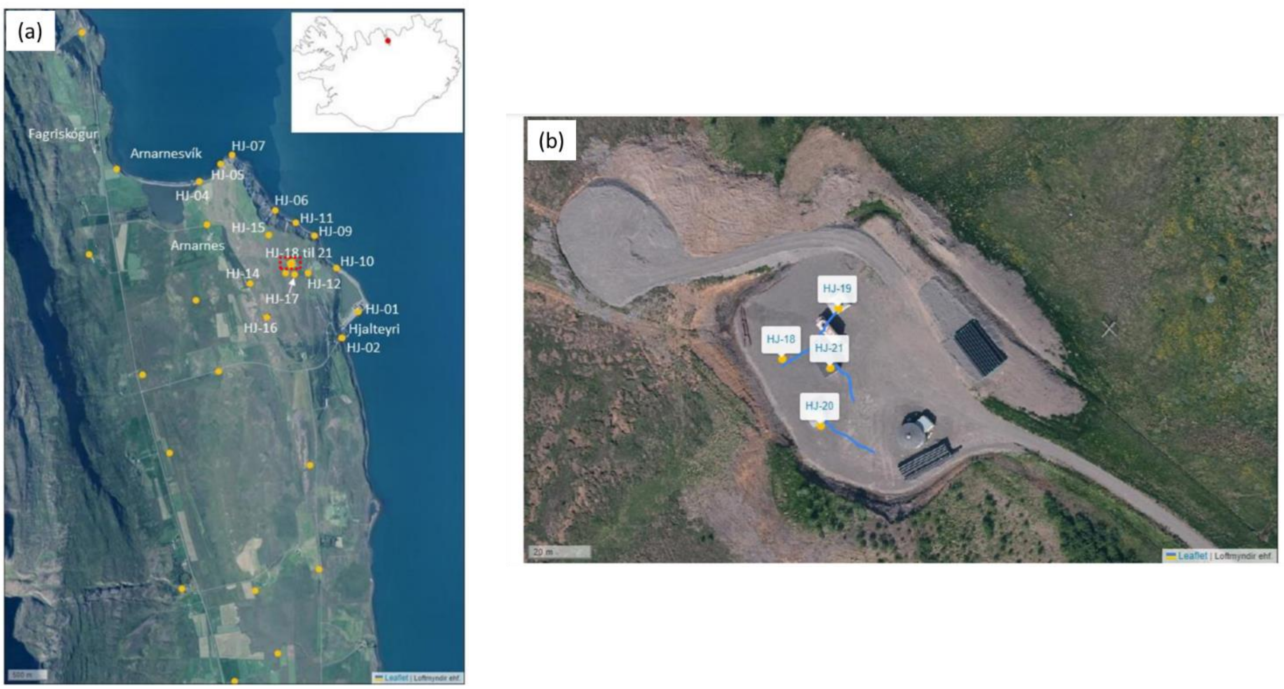


Figure 5: The Hjalteyri well field (a) and the location of the tree production wells, HJ-19, HJ-20 and HJ-21, and the monitoring well HJ-18, in the center of the field (b).

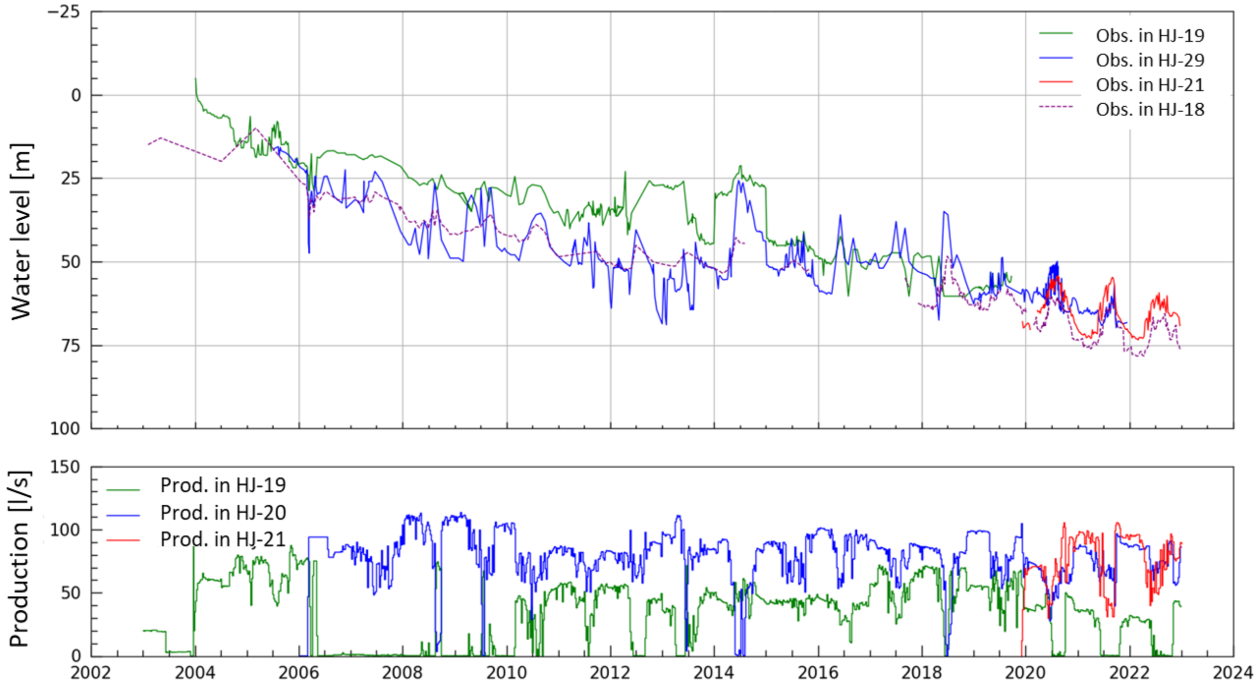


Figure 6: Available production history from the Hjalteyri-reservoir: Production and water level in wells HJ-19, HJ-20 and HJ-21 and water level in HJ-18. From Egilson, 2024).

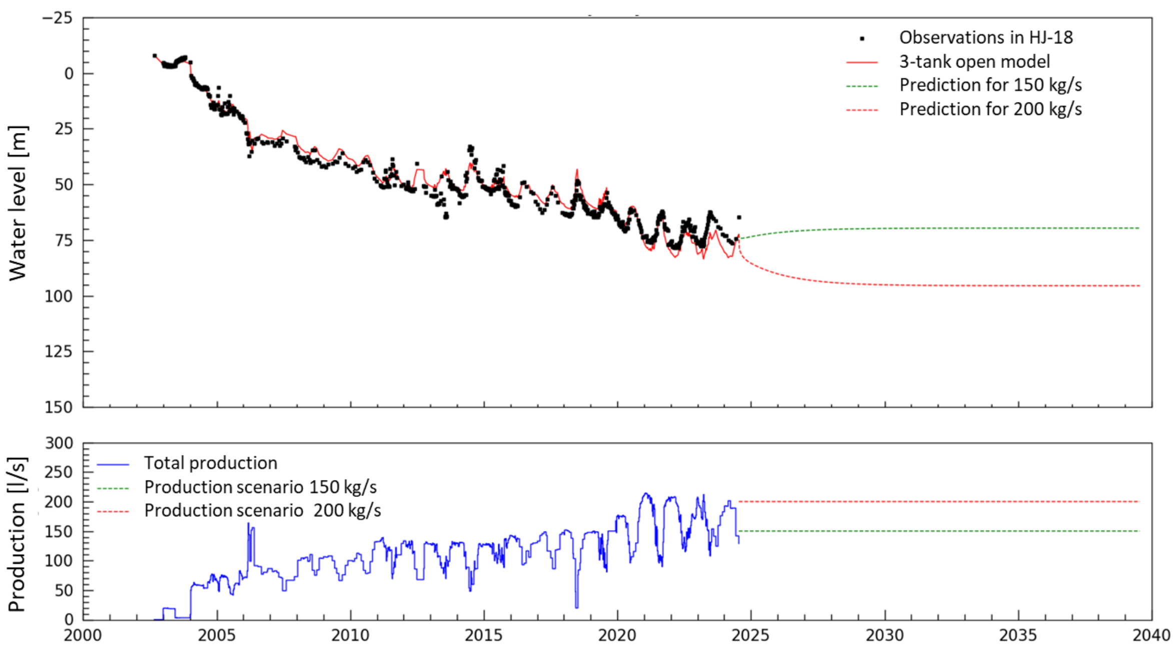


Figure 7: Total production in Hjalteyri-reservoir and water level fitted to the observed water level in well HJ-18 with a 3-tank open Lumpfit v3 model. The predicted water level for two production scenarios, 150 and 200 kg/s for 15 years, is shown. From Egilsson (2024).

3.2 Linear model (Lumpfit v3)

The production response has been modeled with the Lumpfit v3 program at ÍSOR and the latest results are shown in Figure 7. The best fit for the production data was found for a 3-tank open model. According to the predicted water level, the water level in HJ-18 will stabilize between 70-75 m depth and 90-100 m depth for the two production scenarios, 150 and 200 kg/s, respectively. The most recent results shown here, published in ÍSOR reports (Egilsson, 2024; Axelsson et al, 2024), reinforce the finding that the system can sustain an average production of at least 200 kg/s.

3.3 General model (Lumpfit++)

For testing of the newly developed Lumpfit++ software, production data from the Hjalteyri geothermal system was chosen. The available data, production, and water level from four wells, thereof, one observation well, is shown in Figure 6. The wells exhibit a similar production response; however, Egilsson (2024) suggested that production from the most recent well, HJ-21, caused less drawdown— as detected by the observation well HJ-18— than the other production wells. This assumption was based on modeling results from Lumpfit v3, shown in Figure 7, which indicate an increased deviation between the observed and calculated water levels after 2020, when well HJ-21 came on-line.

The data was modeled with Lumpfit++, using a general 5-tank model. To predict water level changes in each of the four wells, each well is placed in its own tank. A fifth tank is added to model the possible effects of the outer parts of the reservoir. The fit between the model and the calculated water level data is shown in Figure 8. The two vertical-slotted red lines shown in the subfigures indicate the data selected for fitting by the model. The predicted water level for an average production of 30, 70 and 60 kg/s, in wells HJ-19, 20 and 21, respectively, is shown in the same figure. The total production adds to 160 kg/s or slightly more than the 150 kg/s scenario calculated with Lumpfit v3. For comparison, the predicted average water level in well HJ-18 becomes stable around 70 m according to the Lumpfit++ model while the Lumpfit v3 model predicts the average water level between 70 and 75 m.

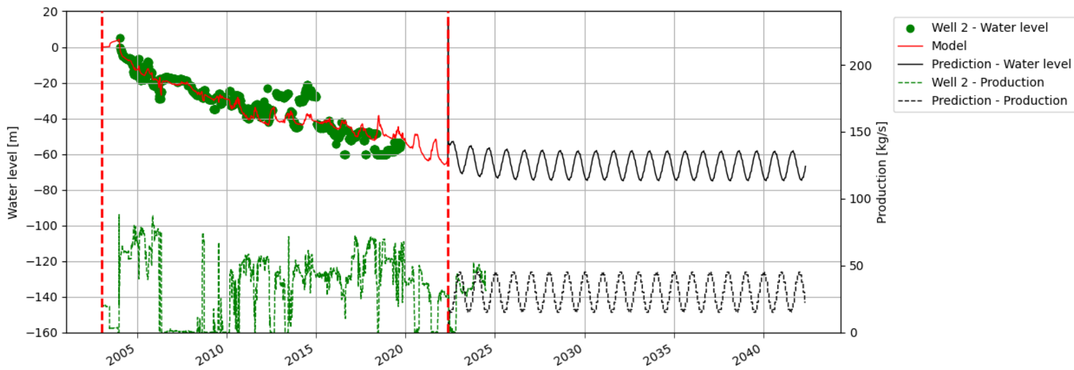
4. CONCLUSIONS

A new software, Lumpfit++, has been developed to fully utilize the so-called Lumpfit method of lumped parameter modeling of pressure changes in geothermal reservoirs, described by Axelsson (1989). A previous version, Lumpfit (original Lumpfit, LUMPFIT 3.1 and Lumpfit v3), has proven to be an effective tool for geothermal system modeling and management (Axelsson, 1989; Axelsson and Arason, 1992). The original software implemented the mathematical model for the subset of linearly connected tanks, whereas the later tool (Lumpfit++) implemented the mathematical model described in Axelsson's original paper for a general system of N-tanks.

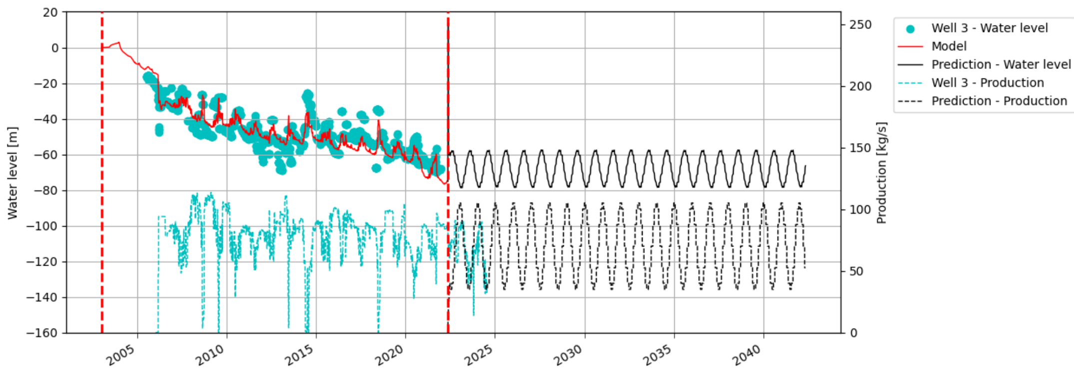
The set of equations for the linear model is described in Axelsson and Arason (1992). The lumped parameters, capacitance (or storage), and conductance (reflecting hydraulic permeability), can be used to estimate the size of the geothermal resource and its permeability given assumptions about the storage mechanism and internal geometry (Axelsson, 1989). Based on Figure 2, tanks 1-3, represent the inner and outer parts of the system, respectively, assumptions about the internal geometry can be based on this.

For the general model, it is non-trivial to relate the lumped parameters to the physical parameters, the storage, and the permeability. This is also beyond the scope of this paper. Furthermore, there are concerns that such models end up being poorly defined in some cases. This is because a system of more than 3 tanks with a variety of possible connections between them, has the possibility of more than one solution fitting the data equally well.

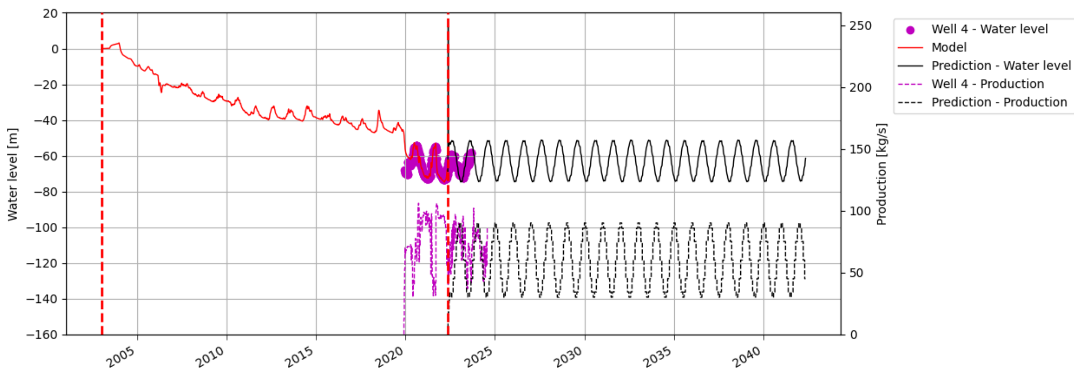
The first modeling of water level from four wells in the Hjalteyri-reservoir N-Iceland with Lumpfit++ is promising. The new software allows for the prediction of the water level in each production well which is important for the management of the system.



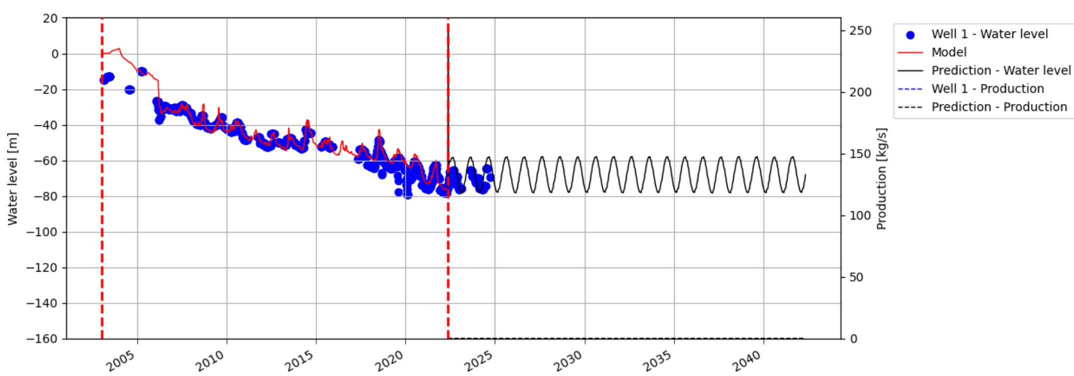
(a) Observed and calculated water level changes in HJ-19



(b) Observed and calculated water level changes in HJ-20



(c) Observed and calculated water level changes in HJ-21



(d) Observed and calculated water level changes in HJ-18

Figure 8: Comparison of observed and calculated water level in wells in Hjalteyri-reservoir N-Iceland. The production history is fitted with a 5-tank Lumpfit++ model and the predicted water level is for a total production of 160 kg/s from the wells.

ACKNOWLEDGMENTS

The work presented is a part of the project "Optimal management of low-temperature geothermal reservoirs – Polish-Icelandic cooperation on reservoir modeling" (acronym GeoModel), financed under the Fund for Bilateral Relations through the European Economic Area Financial Mechanism (EEA FM) and the Norwegian Financial Mechanism (NFM) 2014-2021.

We would like to thank Nordurorka district heating service for allowing the publication of the data from Hjalteyri and for funding part of the work related to the development of the Lumpfit++ software. We also thank Skagafjardarveitur district heating service for allowing the publication of the data from Hrolleifsdalur.

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