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A PREDICTIVE MODEL FOR LOW-ENTHALPY GEOTHERMAL SYSTEMS

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ABSTRACT

Predicting the lifetime of a reservoir is very important for planning and designing a geothermal system. Knowing the system lifetime can help in estimating how economic and viable the system is. It is therefore useful to have a reliable estimate of the system lifetime before starting a detailed study and modelling. This contribution introduces a predictive design model for deep low-enthalpy hydrothermal systems. The model predicts, empirically, the lifetime of a hydrothermal system as a function of reservoir porosity, discharge rate, well spacing, average initial temperature of the reservoir, injection temperature, and cut-off temperature.

In this work, the finite element method was utilized to conduct an extensive parametric analysis on a wide range of physical parameters and operational scenarios for typical hydrothermal regional geometries, from which empirical mathematical relationships were derived to formulate the model.

The proposed model provides geothermal engineers and decision makers with a simple calculation tool (a single equation) capable of giving them a preliminary conjecture about the lifetime of deep low-enthalpy hydrothermal systems.

1. INTRODUCTION

Geothermal heat is an important potential source of renewable energy that is sustainable and generates minimal CO_2 emissions. Hydrothermal systems (also known as geothermal doublets) are the most common method of geothermal energy recovery that utilize two wells; one for hot water production and another for cold water injection. By the start of operation, the cooled injected water moves towards the production well and upon thermal breakthrough, the temperature in the production well starts to decline. This event, defines the reservoir lifetime and its energy production. . Thus, an accurate prediction of both the lifetime and energy production of geothermal doublets is essential for the successful design of such systems (Blöcher et al., 2010 & Diaz et al., 2016).

Significant number of studies have identified various factors influencing heat flow in geothermal reservoirs and their lifetime, including: viscosity and density dependence on temperature (Ma & Zheng 2010; Watanabe et al., 2010; Saeid et al., 2014); porosity and permeability (Mottaghy et al., 2010; Chandrasiri Ekneligoda & Min 2013; Vogt et al., 2013; geothermal fluid salinity (Saeid et al., 2013); flow rate (Franco et al., 2014); well spacing (Sauty et al., 1980); injection temperature (Bedre & Anderson, 2012), and reservoir geometry (Sippel et al., 2013). These studies qualitatively identified the significance of the examined parameters on the lifetime of geothermal systems. This paper focuses on combining these factors in a simple mathematical formulation.

The objective of this work is the development of a predictive model capable of estimating the lifetime of how-enthalpy geothermal systems. The model is suitable for conducting a preliminary design that can be utilized by geothermal engineers and decision makers at an early stage of a project. The model estimates the lifetime as a function of typical physical and system operation parameters, including reservoir porosity, reservoir initial temperature, discharge rate, well spacing, injection temperature, and cut-off temperature. Reaching this objective requires conducting an extensive parametric analysis examining the behavior of the system for different reservoir parameters subjected to different operational scenarios. Details of the model formulation and the finite element discretization are given in Saeid et al., 2015.

2. GOVERNING EQUATIONS

The conceptual physical domain of the geothermal system is decomposed into three sub-domains: I) a porous medium domain, representing a reservoir, surrounding cap layers, and a soil formation immediately above the reservoir; II) two wellbores, representing both an injection and a production borehole; and III) the soil formation above the overburden. The finite element package, COMSOL, has been utilized as a framework to implement the wellbore model and couple it to the geothermal reservoir and the surrounding soil formation. For these, a hybrid modelling technique coupling 1D to 2D and 3D physical geometries has been adopted (details are given in Saeid et al., 2015) .

2.1. Initial and Boundary conditions

The initial temperature of the ground is assumed as:

$$T = 15 + 0.027z \quad (1)$$

in which T_0 is the initial reservoir temperature and z represent height from the surface. Initially, the pressure is assumed hydrostatic.

Dirichlet boundary condition for both heat and fluid flow are considered at the injection well, as:

$$T_{in}(t) = T_{injection} \quad (2)$$

$$Q_{in}(t) = \text{Discharge rate} \quad (3)$$

At the production well, the heat flux and flow rate are prescribed as

$$\lambda_f \frac{dT_p}{d_z} = 0 \quad (4)$$

$$Q_p(t) = - \text{ Discharge rate} \quad (5)$$

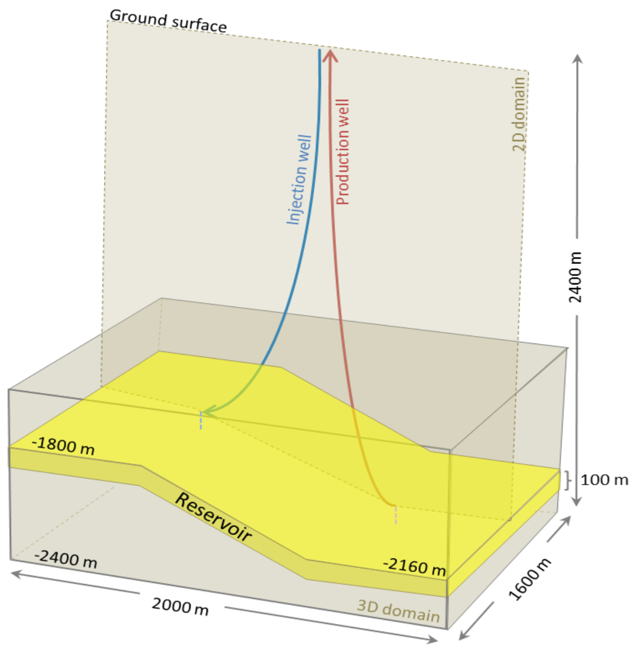

Figure 1- A scheme of the base case (Saeid et al. 2015)

3. CONCEPTUAL MODEL

A schematic presentation of the conceptual model is demonstrated in Figure 1. It represents a deep low-enthalpy geothermal system with dimensions of 2000 m × 1600 m × 2400 m. The reservoir has a thickness of 100 m and located at about 2 km below the ground surface and bounded at the top and bottom by impermeable homogeneous clay layers. It consists of an inclined (20°) homogeneous sandstone with an average porosity of 0.15 and an average permeability of 725 mD ($7.16e^{-13}m^2$).

Table 1. Hydrothermal properties of the conceptual geothermal reservoir model

Parameter	Symbols	Value	Unit
Reservoir			
Permeability	K	725	mD
Porosity	ϕ	15	%
Fluid salinity	S	80	$gr.l^{-1}$
Soil density	ρ_s	2650	$kg.m^{-3}$
Fluid thermal conductivity	λ_f	0.67	$W.m^{-1}.K^{-1}$
Soil thermal conductivity	λ_s	3	$W.m^{-1}.K^{-1}$
Fluid specific heat capacity	c_f	4190	$J.kg^{-1}.K^{-1}$
Soil specific heat capacity	c_s	980	$J.kg^{-1}.K^{-1}$
Adjacent layers			
Soil density	ρ_s	1750	$kg.m^{-3}$
Thermal conductivity	λ_s	2.2	$W.m^{-1}.K^{-1}$
Specific heat capacity	c_s	920	$J.kg^{-1}.K^{-1}$

The wellbores are apart 5 m at the ground surface, and 1 km laterally at the reservoir level. The injection and production discharge is assumed 150 [m^3/h] and the injection temperature is 30 °C. In the base case, the life time is defined as the time when the production well produces a fixed temperature of 60 °C. The rest of the parameters are as given in table 1.

Figure 2 shows a 3D temperature distribution in the reservoir after 25 years of operation.

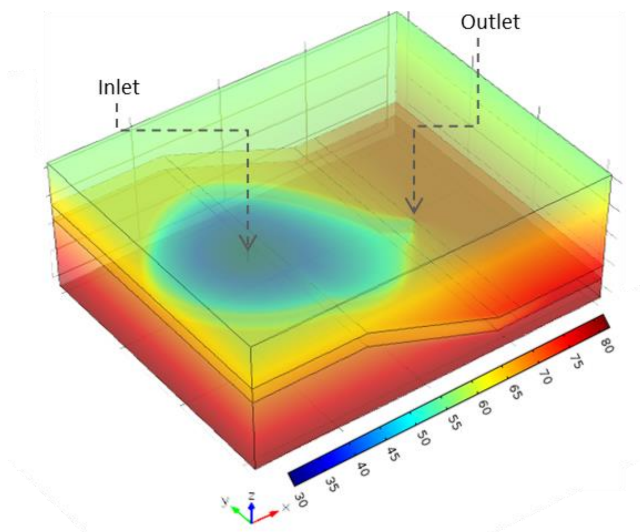

Figure 2. 3D model of cold water front after 25 years (Saeid et al. 2015)

4. PARAMETRIC ANALYSIS

To formulate a design model capable of estimating the lifetime of a geothermal reservoir, an extensive parametric analysis has been conducted. Two issues are considered: 1) determining the significance of the involved parameters, and 2) quantifying the effect of the significant parameters on the system lifetime. The studied parameters are divided into the two categories of physical, and operational parameters. These parameters together with their variation range are listed in Table 2.

Table 2. Parameters for sensitivity analysis and their range of variation in this study. Base case values are colored in orange.

Physical parameters						
Reservoir initial temperature[°C]	70	76	80	85		
Reservoir dip angle	0	20	30			
Salinity[gr/l]	40	80	160			
Effective porosity[-]	0.1	0.15	0.2	0.3		
Operational parameters						
Injection temperature[°C]	30	35	40	50		
Well spacing[km]	1	1.2	1.5	1.8	2	2.5
Discharge rate [m^3/h]	50	100	150	250		
Cut-off Temperature [%]	70	75	80	85	90	95

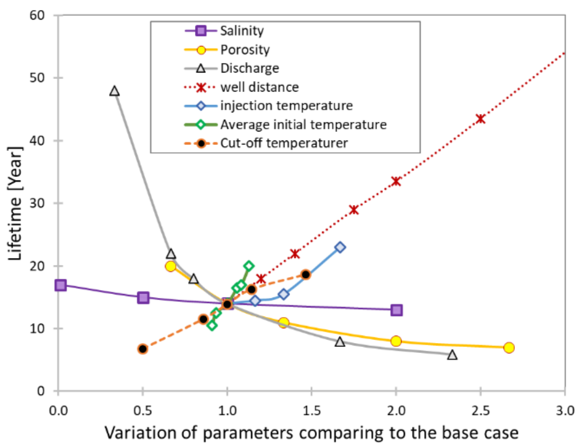

Figure 3. Sensitivity of parameters regarding to the base case.

The parametric analysis is performed by varying one parameter at a time, while keeping the rest at the constant base case values. The lifetime of the system was taken as the criterion.

In Saeid et al 2015 details of the parametric analysis are studied intensively. Figure 6 summarizes the effect of the presented parameters in Table 2 on the life time of the studied reservoir.

5. PREDICTIVE MODEL

The lifetime of a reservoir is an important criterion for planning and designing a geothermal system. It describes how long a geothermal system can operate while providing a desirable energy. That can help in estimating how economic and viable the system is. It is therefore useful to have a reliable estimate of the system lifetime before starting a detailed study and modelling. In this section, a predictive model capable of predicting the lifetime of a low-enthalpy hydrothermal system is introduced. The model formed based on the outcome of the parametric analysis, which has been carried out in previous section.

The parametric analysis showed that among all the studied physical and human controlled parameters; reservoir porosity, discharge rate, well spacing, average initial temperature of the reservoir, cut-off temperature, and injection temperature have a significant impact on the reservoir lifetime. They can be optimized to obtain the highest lifetime with the highest energy production rate.

Knowing these parameters and intensity of their effect on geothermal reservoir lifetime, a mathematical model can be derived which relates all six significant parameters to the reservoir lifetime. For this, several simulation were carried out on the base case with varying porosity, discharge, well spacing, initial, injection temperature, and cut-off percentage.

The model is formulated first by correlating the lifetime to the porosity and discharge. Then, the lifetime is weighted by adding the effect of well spacing, reservoir initial temperature, injection temperature, and cut-off percentage.

5.1. Lifetime as a function of porosity and discharge

To study the co-relation between the reservoir porosity and discharge and the system's lifetime, several simulations were carried out with varying porosity between 0.1 and 0.4, and discharge between 50 m^3/h and 250 m^3/h. Figure 4 demonstrates the variation of lifetime with discharge at different porosities. An exponentially decreasing trend is being seen in these relationships that can elegantly be put in a mathematical model. All curves can be expressed in a general form as

$$L = a + b e^{-Q/c} \tag{6}$$

in which L represents the lifetime in years, and Q represents the discharge in m^3/h. a, b and c are constants to be determined.

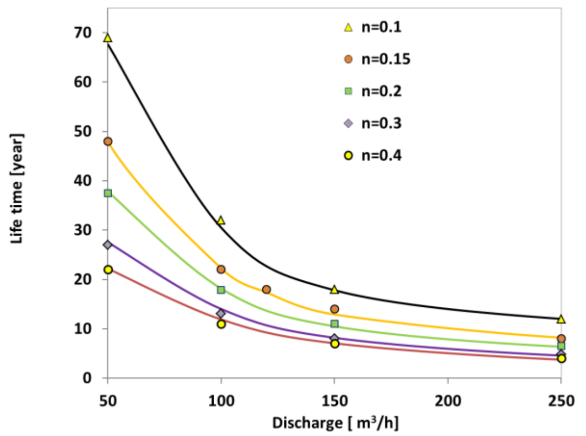

Figure 4- Lifetime vs. discharge and porosity (Saeid et al. 2015)

The fitting curve for each set is expressed as

$$\begin{aligned} n &= 0.1 \quad ; \quad L = 11.25 + 165e^{-Q/46.5} \\ n &= 0.15 \quad ; \quad L = 7.5 + 110e^{-Q/50} \\ n &= 0.2 \quad ; \quad L = 5.6 + 82.5e^{-Q/53} \\ n &= 0.3 \quad ; \quad L = 3.75 + 55e^{-Q/60} \\ n &= 0.4 \quad ; \quad L = 2.8 + 41.2e^{-Q/65.5} \end{aligned} \tag{7}$$

where, apparently, a, b and c are functions of porosity. Parameter a represents the lifetime of the reservoir at "infinitely" high discharge, and parameter b represents the lifetime at small discharge (adding to it a). Inspecting Eqs.(6) and (7), it can be seen that these parameters are directly related to the porosity, such that:

$$\begin{aligned} a &= \frac{1.125}{n} \\ b &= 14.7a = \frac{16.53}{n} \end{aligned} \tag{8}$$

Parameter c represents the shape of lifetime decay with increasing discharge. Figure 6-A shows a linear relationship between parameter c and porosity. It can be described as

$$c = 40.207 + 63.45n \tag{9}$$

Collecting all terms together, gives:

$$L_1 = \frac{1.125}{n}\left(1 + 14.7e^{-Q/(63.45n + 40.207)}\right) \tag{10}$$

in which L_1 is the systems lifetime (year), a function of discharge Q m^3/h and reservoir porosity n. This relationship represents the base model that needs to be modified to include well spacing, reservoir initial temperature and injection temperature.

5.2. Lifetime as a function of porosity, discharge and well spacing

Well spacing is an important parameter that needs to be taken into consideration in the design and lifetime prediction of a low-enthalpy hydrothermal system. It has a linear relationship with lifetime, as has been shown in Figure 3. In order to add its effect to Eq.(10), a series of simulations were carried out.

Four cases have been defined based on the base case with 4 different well spacing (1000, 1750, 2000, and 2500 [m]). Discharge rate has been altered in these four cases to 50, 100, 150, and 250 [m^3/h]. In all these 16 cases, the lateral location of the production well has been varied, while its depth, and thus the initial temperature, is kept constant. Figure 5 shows the different sets and the fitted curves. By inspecting the curves in this figure, it can be seen that the curves have a similar exponential decay as that in Figure 4. Therefore, the effect of the well spacing can be included as a multiplier in equation, Eq. (10). The multiplier for each fitted curve is plotted versus well spacing in Figure 6-B . This figure shows a linear relationship between the multiplier and the well spacing that can be described as

$$M_{ws} = 1.672 \times 10^{-3} ws - 0.668 \tag{11}$$

Adding this multiplier to Eq.(10), gives

$$L_2 = M_{ws} L_1 \tag{12}$$

in which L_2 is the lifetime of the reservoir as a function of discharge, porosity and well spacing (ws).

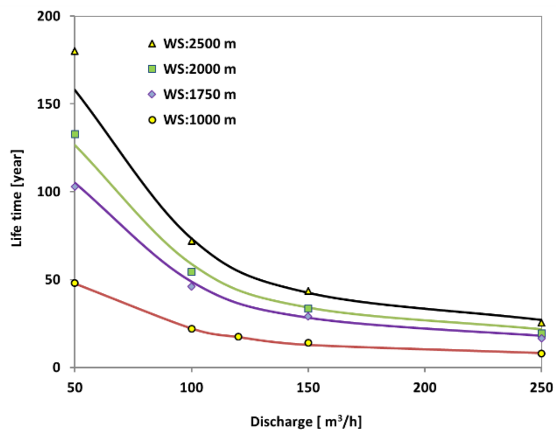

Figure 5- Lifetime vs. discharge and well spacing (Saeid et al. 2015)

5.3. Lifetime as a function of discharge, porosity, well spacing and initial temperature

The initial temperature of the reservoir plays an important role in the heat transfer process in the system, and therefore on its lifetime.

Similar to the well spacing effect, the effect of the reservoir initial temperature can be included in the model by incorporating a proper multiplier to Eq. (12) .The multiplier is obtained by adjusting the curves to fit the different combination of initial temperatures and discharges. Figure 6-C shows a linear relationship between the fitted multipliers and the reservoir initial temperatures. The initial temperature of the reservoir is taken, in case of an inclined reservoir, as the average between the top and bottom temperature of the reservoir. This relationship can be described as

$$M_{T_r} = 0.0415 T_r - 1.7635 \quad (13)$$

in which T_r (ºC) is the average initial reservoir temperature. The multiplier is added to Eq. (12) to obtain the lifetime as a function of discharge, porosity, well spacing, and average initial reservoir temperature, such that

$$L_3 = M_{Tr} L_2 \quad (14)$$

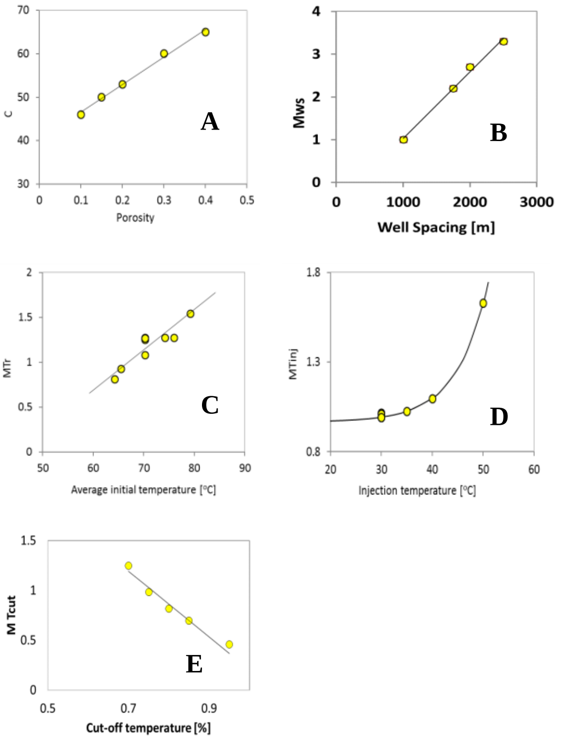

Figure 6. A) Parameter *c* as a linear function of porosity. B) multiplier vs. well spacing. C) multiplier vs. average initial reservoir temperature. D) multiplier vs. injection temperature. E) multiplier vs. cut-off temperature percentage.

5.4. Lifetime as a function of discharge, porosity, well spacing, initial temperature and injection temperature

As the injection temperature of a geothermal system increases, its lifetime is also increases. Similar to previous parts, a multiplier is added to L3 to demonstrate injection temperature effect on reservoir lifetime. An exponential relationship between the multipliers and the injection temperature can be found. As:

$$M_{T_{inj}} = 0.96621 + 0.0002112\, e^{(0.16103 T_{inj})} \quad (15)$$

in which T_{inj} (ºC) is the injection temperature and M_{Tinj} is the injection temperature multiplier. This multiplier is incorporated into Eq. (14), giving:

$$L_4 = M_{T_{inj}} L_3 \quad (16)$$

5.5. Lifetime as a function of discharge, porosity, well spacing, initial temperature, injection temperature and cut-off Temperature

Cut-off temperature is another parameter which effect reservoir lifetime. It can be defined differently in each project depending on initial reservoir temperature, energy demand, and surface facilities including heat exchangers. Here cut-off temperature is defined as a percentage of the initial temperature at the production well, as: 95%, 90%, 85%, 80%, 75%, and 70%. Cut-oof temperature effect of the reservoir lifetime can also be considered as a multiplier to L4, as:

$$M_{T_{cut}} = -3.2 T_{Cut\%} + 3.5 \quad (17)$$

$$T_{Cut\%} = \frac{T_{cutoff}}{T_{p(t=0)}} \quad (18)$$

In this equation, T_{Cut}% represents the cut-off temperature with respect to the initial temperature at the production well. T_{cutoff} is the cut-off temperature for which geothermal reservoir lifetime will be defined. This multiplier is incorporated into Eq. (19), giving:

$$L_5 = M_{T_{cut}} L_4 \quad (19)$$

5.6. Design model

Collecting all terms, a prototype design model describing the system lifetime as a function of discharge, porosity, well spacing, initial temperature and injection temperature can be expressed as

$$L = M_{ws} M_{Tr} M_{T_{inj}} M_{T_{cut}} \frac{1.125}{n} \left(1 + 14.7 e^{-Q/(63.45 n + 40.207)}\right) \quad (20)$$

in which

$$M_{ws} = 1.672 \times 10^{-3} ws - 0.668$$

$$M_{T_r} = 0.0415 T_r - 1.7635$$

$$M_{T_{inj}} = 0.96621 + 0.0002112\, e^{(0.16103 * T_{inj})}$$

$$M_{T_{cut}} = -3.2 T_{Cut\%} + 3.5$$

6. MODEL VERIFICATION

All scenarios that have been calculated using COMSOL, are re-calculated here using the proposed prototype design model (Eq. (20)). The calculation results of both approaches are plotted in Figure 7 (red circles). Apparently, there is a good match between the two models. The average error for all data points in Figure 7 is within 7%.

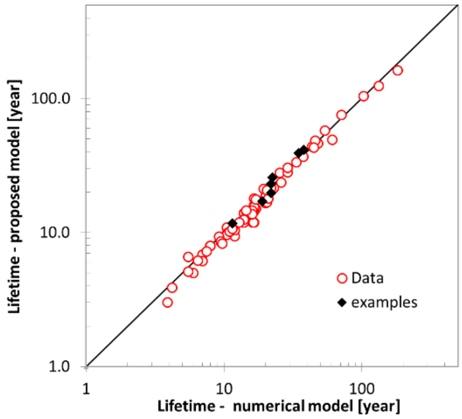

Figure 7. Lifetime calculated by proposed model versus lifetime calculated by numerical model

To verify the proposed predictive model against scenarios which are not considered in the curve fitting, a couple of extra scenarios have been modelled numerically and their lifetimes are compared with the value calculated by Eq. (20). The lifetime of these scenarios are included in Figure 7 and shown as black diamonds. The figure shows that they have a reasonable match with an average error of 9%. More details about these cases can be found in Saeid et al. 2015.

7. MODEL CONSTRAINTS

Overall, it can be concluded that the proposed prototype model is capable of predicting the lifetime of a deep low-enthalpy geothermal system within 9% error. However, it must be noticed that the proposed model is valid for the range of parameters utilized in the parametric analysis. Beyond this range, the model may not be valid. The parameters ranges are:

- Porosity: from 0.1 to 0.4
- Discharge: from 50 to 250 m^3/h
- Well spacing: from 1000 to 2500 m ; one doublet
- Average initial temperature: from 65 to 80 ^{o}C
- Injection temperature: from 30 to 50 ^{o}C
- Lifetime temperature limit: between 70-95% of initial production temperature
- System control mode: discharge rate in both wells

Therefore, in order to cover a wider range, other cases with different scenarios need to be studied.

8. CONCLUSIONS

In this paper, a predictive model for deep low-enthalpy hydrothermal systems is introduced. The model predicts, empirically, the lifetime of a hydrothermal system as a function of reservoir porosity, discharge rate, well spacing, average initial temperature of the reservoir, injection temperature, and cut-off temperature percentage. The finite element package COMSOL was utilized to conduct an extensive parametric analysis on a wide range of physical parameters and operational scenarios for typical hydrothermal regional geometries, from which empirical mathematical relationships were derived to formulate the model.

The proposed model provides geothermal engineers and decision makers with a simple calculation tool capable of giving them a preliminary conjecture about the lifetime of a deep low-enthalpy hydrothermal system. It provides researchers and designers an introduction to a modelling technique that can be utilized to derive more elaborate models which cover more parameters and a wider range of applications.

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