

Investigating the long-term thermal response of mine water geothermal systems through parametric numerical analyses

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ABSTRACT: Flooded abandoned mines are increasingly recognized as a valuable source of low-carbon geothermal energy, particularly in urban areas where sustainable heating systems are needed. These subsurface reservoirs offer stable temperatures and proximity to heat demand, positioning them as a promising alternative to conventional energy sources. While the concept has gained momentum in recent years, further research is needed to better characterize the long-term thermal behaviour of mine water geothermal systems under different design and operational conditions. A three-dimensional numerical model, developed using the finite element method and calibrated with field data from the UK Geoenery Observatory in Glasgow, was used to investigate the thermo-hydraulic behaviour of these systems. Parametric simulations were conducted to evaluate the influence of flow rate, reinjection temperature, and bedrock thermal conductivity on abstraction temperatures over a 20-year operational period. Results indicate that bedrock thermal conductivity plays a minor role under typical conditions, but its influence may increase in mine layouts featuring extensive rock–water interfaces, such as pillar-and-stall geometries. In contrast, reinjection temperature and flow rate have a more pronounced impact: lower reinjection temperatures and higher flow rates enhance short-term heat extraction but accelerate long-term thermal decline. Under scenarios with equal heat extraction, higher temperature differences combined with lower flow rates contributed to greater thermal stability over time. These findings revise earlier assumptions that prioritized flow rate maximization and highlight the importance of balancing thermal performance with long-term sustainability. The presented modelling framework offers a valuable tool for optimizing mine water geothermal systems and supports their broader integration into urban energy strategies.

KEYWORDS: Abandoned mines, shallow geothermal energy, thermal sustainability, numerical modelling.

1 INTRODUCTION

The increasing demand for sustainable and low-carbon heating solutions has driven interest in the reuse of flooded abandoned mines as geothermal reservoirs, particularly in urban areas. These subsurface voids, originally formed by historical mining activities and later refilled with groundwater, offer stable thermal environments and are often located near population centres. Their favourable thermal properties and spatial distribution make them attractive for use in district-scale heating and cooling applications via heat pump systems.

Despite growing interest, the broader adoption of mine water geothermal systems remains limited. One reason is the presence of key uncertainties associated with subsurface conditions following mine closure. Challenges include predicting the behaviour of water flow and heat transport in complex underground geometries, as well as the potential for thermal breakthrough and gradual performance decline over long-term operation (Walls et al. 2021, Monaghan et al. 2025). These knowledge gaps highlight the need for more detailed investigations that can support the reliable design and operation of such systems.

To address this, the present study employs a validated three-dimensional numerical model developed using COMSOL Multiphysics v6.3 and calibrated with field data from the UK Geoenery Observatory (UKGEOS) in Glasgow (Polat et al. 2025). Particular focus is placed on three key parameters: flow rate, reinjection temperature, and bedrock thermal conductivity, which are varied independently to assess their individual and combined influence on abstraction temperature over a 20-year period. Additionally, scenarios involving equivalent heat extraction are explored by adjusting flow rates and temperature differences, allowing for the evaluation of thermal performance under realistic operational constraints. The findings aim to inform future design strategies for mine water geothermal

systems, with emphasis on long-term performance and sustainability.

2 OVERVIEW OF THE NUMERICAL MODEL

The numerical model was developed using COMSOL Multiphysics and is based on the UK Geoenery Observatory (UKGEOS) Glasgow Research Site, established by the British Geological Survey. As the world's first observatory dedicated to monitoring shallow mine water geothermal systems, UKGEOS provides extensive subsurface characterization and test data, which enabled validation of the model (Polat et al., 2025). For the purposes of the current parametric analyses, a number of modifications were introduced to the validated model. These adjustments are detailed in the following sections.

2.1 Model Setup

The numerical simulations were based on the Glasgow Upper (GU) mine working, which served as the reference mine for model validation in prior work. Two boreholes, GGA01 and GGA07, screened within the GU mine seam and equipped with submersible pumps, were modelled to represent injection and abstraction wells, respectively. These boreholes are spaced approximately 135 m apart.

While operational geothermal systems often employ reinjection and abstraction from different seams to reduce thermal interference (Banks et al. 2022, Verhoeven et al. 2014), the existing site geometry and borehole configuration at UKGEOS were retained in this study. As the objective is to investigate thermal behaviour under different parameter combinations, rather than to evaluate system feasibility, preserving the validated setup ensures consistency.

Model validation (Polat et al., 2025) was performed using a pumping test and a geothermal operation test conducted on GGA01. The simulated results were compared against field

observations, with particular attention given to drawdown behaviour during pumping and recovery and recovery temperatures observed near the reinjection borehole during geothermal operation, as these were the only measurable outcomes available from the field tests for model validation. These comparisons confirmed that the model reliably reproduced the hydraulic and thermal responses observed in the field. The material properties used for validation were obtained from the literature (Gonzalez Quiros et al. 2024, Monaghan et al. 2017, Gonzalez Quiros & Boon 2023), summarized in Table 1, and also adopted in this study.

The coupled thermo-hydraulic processes were modelled using the finite element method, incorporating (i) Darcy's Law for subsurface flow, (ii) Heat Transfer in Porous Media to simulate conductive and advective heat transport, and (iii) Well and Line Heat Source features to represent injection-abstraction processes at borehole locations.

The initial temperature was set to 12 °C based on field measurements at the GU mine working. Lateral groundwater flow was intentionally excluded to eliminate location-specific thermal recharge effects and focus solely on parameter-driven thermal responses.

Table 1. Material properties applied in the model.

Property	Sandstone	Fractured bedrock	GU Mine Working	Mudstone
Density (kg/m ³)	2400	2000	1500	2400
Heat Capacity (J/kgK)	850	900	1300	850
Intrinsic Permeability (m ²)	1×10 ⁻¹²	5.39×10 ⁻¹¹	1.08×10 ⁻⁹	1×10 ⁻¹⁴
Porosity	0.1	0.25	0.30	0.1

2.2 Parameter Selection and Simulation Configuration

The parametric analysis focuses on three key parameters: injection-abstraction flow rate, reinjection temperature, and thermal conductivity of the bedrock.

For the injection-abstraction flow rate, constraints defined by the Scottish Environment Protection Agency (SEPA) were considered (Monaghan et al. 2022). The maximum permitted discharge rate at the site is 20 L/s. Given the relatively short distance between the injection and abstraction boreholes, more conservative values were selected to reflect likely operational limits. The values used in the analysis were 5, 7.5, and 10 L/s and were kept constant throughout each simulation.

The selection of reinjection temperatures was based on the initial mine water temperature and typical temperature differences (ΔT) used in applications (Gluyas et al. 2020). Thus, three different scenarios were modelled with ΔT values of 3, 5, and 7 °C, corresponding to reinjection temperatures of 9, 7, and 5 °C, respectively. It should be noted that only a heating operation was simulated in this study, with reinjection temperatures set below the in-situ mine water temperature to represent heat extraction from the subsurface.

For bedrock thermal conductivity, laboratory measurements from various geological units, sandstone, mudstone, and limestone, at the site yielded values ranging from 2.42 to 3.49 W/mK (Gonzalez Quiros & Boon 2023). Based on these data, three representative values were selected for the simulations: 2.5, 3.0, and 3.5 W/mK. To isolate the effect of thermal conductivity, these values were applied uniformly across all bedrock units in each simulation, thereby eliminating the influence of varying lithological thicknesses.

To evaluate the influence of each parameter independently, the other two parameters were held constant at their middle

values. Accordingly, the base case was defined using a bedrock thermal conductivity of 3.0 W/mK, a flow rate of 7.5 L/s, and a reinjection temperature of 7 °C. All simulation scenarios are summarized in Table 2.

Each scenario was simulated over a 20-year period to assess long-term thermal behaviour. The primary output used for comparison was the evolution of abstraction temperature over time.

In addition to the main parameter variations, three additional simulations were conducted using the previously defined reinjection temperatures, but with adjusted flow rates that ensured equivalent heat extraction across investigated scenarios. These cases were included to assess how thermal performance varies when heat extraction is held constant through flow rate–temperature coupling, and the results were compared accordingly.

Table 2. Selected parameters and values.

Parameters	Unit	Min	Base Case	Max
Flow Rate	L/s	5	7.5	10
Reinjection Temperature	°C	5	7	9
Thermal Conductivity of Bedrock	W/mK	2.5	3	3.5

3 RESULTS AND DISCUSSIONS

Before discussing the effects of individual parameters, the system's general thermal response is illustrated using a representative base case scenario. This case corresponds to a bedrock thermal conductivity of 3.0 W/mK, a reinjection–abstraction flow rate of 7.5 L/s, and a reinjection temperature of 7 °C, values positioned near the midpoints of the selected parameter ranges.

Figure 1 presents the abstraction temperature over a 20-year simulation period, while Figure 2 shows the corresponding temperature distribution within the mine workings at the end of the simulation. A gradual decline in abstraction temperature is observed, reaching approximately 9.84 °C at year 20. The results show a distinct thermal plume forming between the reinjection and abstraction boreholes, indicating the main zone of heat exchange. Due to the short distance between the boreholes and their location within the same mine seam, thermal interference occurs relatively quickly, resulting in a noticeable decline in abstraction temperature over time.

However, it should be noted that this study does not aim to assess the feasibility of the UKGEOS Glasgow site for operational use. The current model setup is used for research purposes to enable systematic parametric analysis, rather than to represent an optimized design for real-world implementation.

The effects of each parameter on the abstraction temperature are discussed in detail in the following subsections.

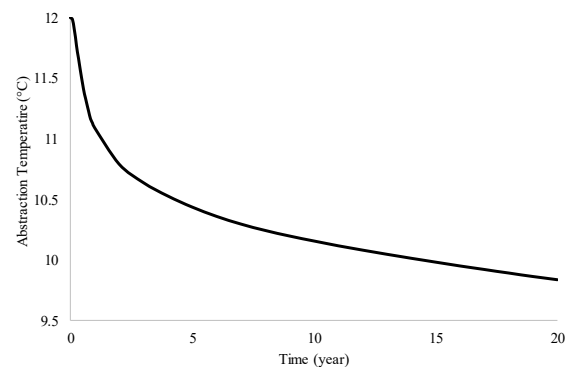


Figure 1. Abstraction temperature for 20 years of constant operation for base case.

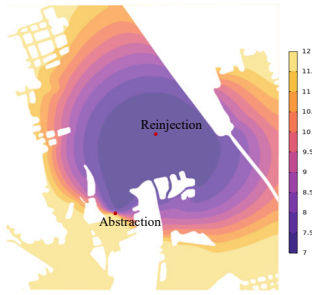


Figure 2. Temperature distribution around the injection and abstraction points within mine after 20 years of constant operation. White zones represent unmined coal. Based upon Data provided by the British Geological Survey © UKRI. All rights reserved.

3.1 Effect of Flow Rate

Figure 3 presents the abstraction temperature over a 20-year period for different flow rate scenarios, with the reinjection temperature fixed at 7 °C and the bedrock thermal conductivity set to 3.0 W/mK. As shown in the figure, increasing the flow rate leads to a reduction in the abstraction temperature. For example, at a flow rate of 5 L/s, the abstraction temperature at year 20 is approximately 10.06 °C, while it is 9.67 °C for a flow rate of 10 L/s, representing a 3.3% lower abstraction temperature.

This trend is expected, as higher flow rates, combined with a constant reinjection temperature, result in increased heat extraction from the mine water system. The greater volume of cooler water being circulated through the system accelerates heat removal, thereby lowering the abstraction temperature over time.

These results highlight the trade-off between short-term thermal output and long-term thermal sustainability. While higher flow rates allow for more immediate heat extraction, they may lead to faster thermal depletion of the system if not carefully managed.

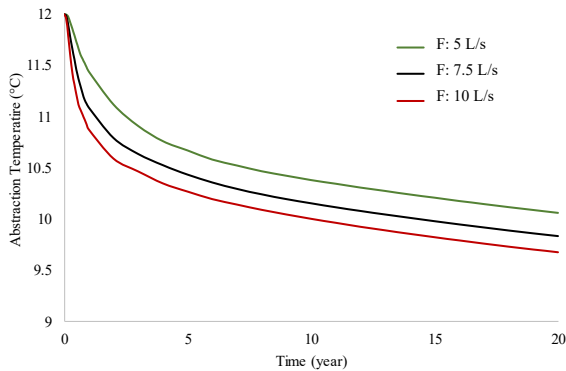


Figure 3. Abstraction temperatures for 20 years of constant operation with different flow rates.

3.2 Effect of Reinjection Temperature

Figure 4 shows the abstraction temperature over a 20-year period for different reinjection temperature scenarios, with the flow rate fixed at 7.5 L/s and bedrock thermal conductivity set to 3.0 W/mK. As expected, lower reinjection temperatures result in greater cooling of the system, leading to lower abstraction temperatures over time.

This behaviour is driven by the increasing temperature difference (ΔT) between the initial mine water temperature and the reinjection temperature. A larger ΔT enhances the heat extraction rate, thereby accelerating the thermal depletion of the system.

For example, a reinjection temperature of 9 °C results in an abstraction temperature of 10.68 °C at year 20, while a

reinjection temperature of 5 °C leads to an abstraction temperature of 9.03 °C, representing a reduction of approximately 14%. These results emphasize the strong influence of reinjection temperature on long-term thermal performance.

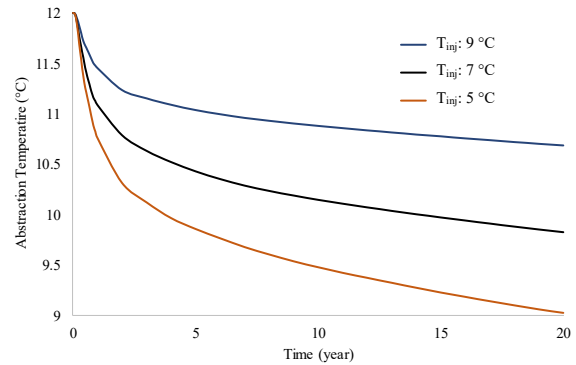


Figure 4. Abstraction temperatures for 20 years of operation with different reinjection temperatures.

3.3 Effect of Bedrock Thermal Conductivity

Figure 5 presents the abstraction temperature over a 20-year period for different values of bedrock thermal conductivity, analysed separately for two flow rate scenarios. As shown in the figure, variations in thermal conductivity alone have a relatively minor effect on long-term abstraction temperature. For example, at a flow rate of 5 L/s, increasing the bedrock conductivity from 2.5 W/mK to 3.5 W/mK results in only about a 0.3% change in abstraction temperature after 20 years.

Interestingly, this difference becomes even less significant at higher flow rates. This trend can be explained by the lower exposure time of the fluid to the surrounding bedrock at increased velocities, which reduces the potential for conductive heat transfer. As a result, the influence of the bedrock's thermal conductivity on abstraction temperature diminishes.

Additionally, the limited impact of thermal conductivity in this case may be linked to the specific geometry of the mine system. The model represents a relatively continuous mine volume, rather than a network dominated by roadways or tunnels. As a result, the bedrock–water interface area is relatively small, limiting the potential for conductive heat transfer through the surrounding bedrock mass. In contrast, if the site consisted primarily of galleries with more surface area relative to volume, the influence of bedrock thermal conductivity would likely be more pronounced.

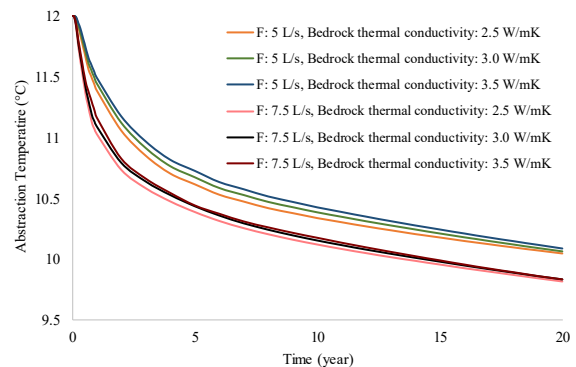


Figure 5. Abstraction temperatures for 20 years of constant operation with different thermal conductivities for two flow rates.

3.4 Thermal Response under Equivalent Heat Extraction Conditions

In this section, the thermal response of the system is investigated under equivalent heat extraction conditions,

aiming to assess the effect of different combinations of reinjection temperature and flow rate. To ensure a consistent heat extraction rate, three scenarios were defined with ΔT values of 3°C, 5°C, and 7°C, corresponding to flow rates of 12.5 L/s, 7.5 L/s, and 5.36 L/s, respectively. All other parameters were kept the same as in the base case, to isolate the influence of the flow rate–temperature coupling on long-term thermal performance.

The results are presented in terms of thermal performance, a dimensionless parameter ranging from 0 to 1, which reflects the rate of change in ΔT over time. A thermal performance value of 1 indicates that there is no change in ΔT (i.e., the abstraction temperature remains stable), while lower values indicate a reduction in performance due to a decline in abstraction temperature. As shown in Figure 6, systems with higher ΔT and lower flow rates tend to maintain higher thermal performance over time, indicating better long-term thermal stability.

These findings emphasize that, beyond meeting the thermal energy demand, the coupling of reinjection temperature and flow rate plays a critical role in sustaining thermal performance and should be carefully considered during the design process.

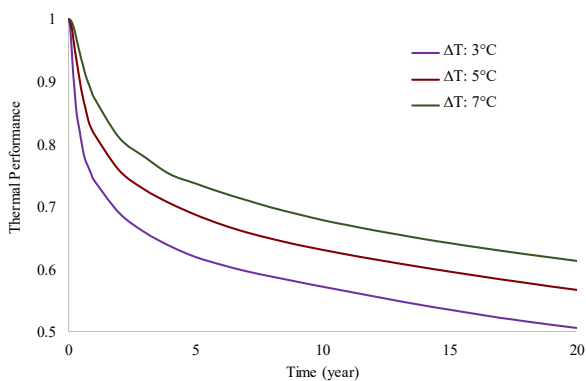


Figure 6. Thermal performance of the system under equivalent heat extraction conditions.

4 CONCLUSIONS

A numerical model, developed using COMSOL Multiphysics and based on the UKGEOS Glasgow Research Site, was employed to investigate the thermal response of a shallow mine water geothermal system over a 20-year period. The parametric study focused on the effects of, injection–abstraction flow rate, reinjection temperature, and bedrock thermal conductivity, each of which varied independently to isolate its influence.

The results indicate that variations in bedrock thermal conductivity have a relatively limited effect on abstraction temperature, especially at higher flow rates where there is less opportunity for heat exchange between the bedrock and water. However, this influence can vary depending on the mining method; in mines developed with pillar and stall technique, the larger bedrock–water contact surface may increase the role of conductive heat transfer and amplify the effect of thermal conductivity. In contrast, flow rate and reinjection temperature have more pronounced impacts: higher flow rates and lower reinjection temperatures lead to increased heat extraction but also faster thermal depletion of the system.

Additionally, scenarios with equivalent heat extraction, achieved by adjusting flow rates according to ΔT , revealed that systems with higher ΔT and lower flow rates maintain improved long-term thermal performance. This emphasizes the importance of optimizing both temperature difference and flow rate in geothermal system design, not only to meet energy demand but also to enhance thermal sustainability.

These findings underscore the value of systematic numerical modelling in informing design strategies for shallow mine water geothermal applications, particularly in the context of long-term operation and planning. It should be noted, however, that this study represents a parametric analysis conducted on a research site. In future work, a more comprehensive assessment should be carried out on a site with actual operational potential, using scenarios that are tailored to the realistic heat demand profiles of the surrounding area. This would allow for more accurate evaluation of system feasibility and design optimization under practical conditions.

5 ACKNOWLEDGMENTS

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