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Evaluating Sustainable Heat Recoverable from Mine Water Geothermal Systems: A Critical Assessment of Methodological Applicability

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ABSTRACT

Disused flooded coal mines that underlie many highly populated areas worldwide are increasingly used as a low-grade heat source for space heating and cooling, and for seasonal thermal heat storage. This is a proven technology with many systems operating worldwide, but the widespread development of the resource is partly hindered by the difficulty of predicting the available heat and how much can be sustainably recovered in the long term. When assessing other geothermal systems, the fraction of heat recoverable is determined with a suite of methods to estimate a recovery factor. The application of such a concept in mine water systems is not straightforward. Mines are anthropogenically modified and extremely heterogenous systems. The heat recovery depends on the complex interplay between the reservoir characteristics (e.g. extent of interconnected galleries, mining voids and overburden permeability), the hydraulic recharge/discharge and the geothermal infrastructure design. In this paper, we examine why existing methods are not directly applicable to mine water settings and the importance of considering a sustainability factor for mine water geothermal potential assessment. We discuss the main factors controlling the sustainable heat recovery in a mine water geothermal system by qualitatively comparing two types of systems: abstraction with discharge and abstraction with reinjection. We use hydraulic and temperature data from the UK to showcase end members. The results are used to guide towards best practice for the optimization of heat utilization and the choice of the most appropriate geothermal infrastructure design.

1 INTRODUCTION

Mine water geothermal for heating and cooling applications and mine thermal energy storage (MTES) offers opportunities to contribute to the decarbonization of heating, taking advantage of the large volume of stored heat over extensive areas. Tens of successful mine water heat recovery schemes are currently operating worldwide (Walls et al. 2021; Oppelt et al., 2025). Most of the plants installed to this date have a heat output commonly lower than 200 kW and a few with capacities of up to 400 kW. Larger plants able to provide heating and cooling to several facilities have a total capacity ranging between 1 - 6 MW. Some examples include the Fondon and Barredo schemes in Asturias (Spain), or the scheme in Heerlen, Netherlands, a District Heating and Cooling (DHC) network integrating coal mines in operation since 2007. Similar systems are currently being developed in Bochum, Germany. The first large-scale mine water heat network in the UK started operation in 2023, providing up to 6 MW of heat to hundreds of social homes, offices, large public buildings and businesses in Gateshead.

The success of mine water geothermal schemes relies on the ability of the system to sustain a sufficient flow rate at a stable production temperature to provide the required heat energy needs over the long term. In other words, a system can only be viable if the thermal output of a mine meets the heat demand of a nearby consumer and the resource can be accessed and delivered without leading to significant reservoir hydraulic and thermal depletion. This depends on the interplay between a range of reservoir parameters (e.g. volume of interconnected voids) and infrastructure design (e.g. well separation, pumping rate) that must ensure a balance between the abstraction rates and the hydraulic recharge, sufficient flow pathway lengths to prevent thermal breakthrough, chemical contaminations or scaling issues (e.g. Shettleston, UK; Walls et al., 2021).

Determining the heat recoverable and the sustainability of heat recovery is inherently linked to the nature of the system. Focusing on open-loop systems (Figure 1), these can be divided into two main types:

- Abstraction with discharge (e.g. Fondon and Barredo, Spain; Dawdon, UK), usually implemented in mine water treatment schemes. In such systems, the required pumping rate may be driven by the need to maintain the water level below a safety depth, whilst maximum achievable pumping rates (and therefore energy output) are constrained by the rate of natural recharge to prevent hydraulic drawdown.

- Abstraction with reinjection (e.g. Heerlen, Netherlands; Gateshead Energy Company Heat Network, UK; Lanchester Wines, Gateshead at two sites: Abbotsford Road and Nest Road, UK), in the same or a different mine working or section of the 'reservoir'. The reinjection temperature and pumping rate (controlled parameters) must take into consideration the system interconnectivity, with a high connectivity between a well doublet leading to a risk of 'short-circuiting' or thermal breakthrough (i.e. arrival of cold reinjected water to the abstraction well) whilst a sufficient permeability remains essential to achieve flow rates high enough for geothermal utilization.

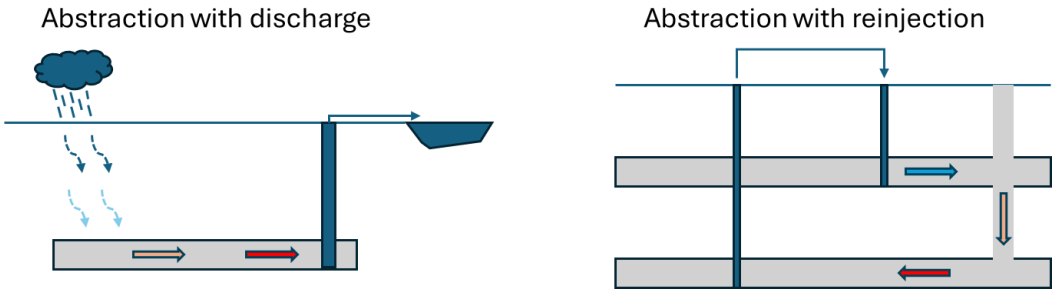


Figure 1 Type of most common mine water geothermal systems (open-loop).

To date, there is no standard approach to determine the heat potential and to predict the amount of heat that can be sustainably recovered from flooded coal mines. Common strategies to characterize a mine water geothermal system include theoretical calculations to estimate the heat in place by considering the volume of water in the voids and the surrounding rock, analysis of hydraulic and thermal monitoring in boreholes and shafts, as well as flow and thermal tests, such as pumping or thermal tracer tests.

The applicability of these traditional geothermal and hydrogeological characterization methods for mine water systems, which have complex geometry, is not straightforward and its application has specific relevance depending on the approach. In this paper we discuss how these methods can be applied to characterize the thermal and hydraulic state of the flooded mine and its potential for geothermal extraction or mine thermal energy storage. We show and compare data from different mine water systems, focusing on the case of flooded coal mines in the UK, to highlight the main characteristics controlling their potential for sustainable heat recovery and/or thermal energy storage. The observations are discussed in terms of their impact and applicability for each case and how they provide information for geothermal use.

2 METHODS

2.1 Mine Water Geothermal Reservoir

This section reviews the different mine water reservoir thermal and hydraulic properties as well as the design characteristics of the geothermal infrastructure controlling the efficiency of heat recovery and sustainability of heat extraction, i.e. heat mined from the system (Figure 2).

2.1.1 Hydraulic Settings

- **Hydraulic properties**. The porosity and permeability/transmissivity of the mine working, goaf (collapsed, compacted material), caved and fractured zones and undisturbed rock.
- **The volume of each zone** (mined, caved, fractured, undisturbed), which defines the total amount of heat stored.
- **The proportion of interconnected voids**. This controls the amount of accessible heat and the rate at which heat can be recovered from each unit. Whilst sufficient interconnectivity is required to ensure access to a large volume of water/rock and avoid significant pressure drawdown/build-up around boreholes, extensive gallery interconnectivity may promote short-circuiting and induce thermal breakthrough.
- **The groundwater abstraction flow rate**. In abstraction with discharge systems, it is directly related to the groundwater balance, i.e. how much can be extracted without causing significant drawdown or conversely, how much needs to be extracted to protect overlying aquifers or control discharges.
- **Groundwater recharge**. In small confined systems, insufficient hydraulic recharge is likely to be the main cause for unsustainable production. In abstraction with reinjection systems, a lack of natural flow might prevent heat dispersion and efficient thermal recharge.

2.1.2 Thermal Settings

- **Thermal Properties.** The reservoir rock thermal conductivity defines the heat exchange rate between the rock and water. The reservoir heat capacity defines the energy that can be released for a given temperature change and depends on the volume of voids and rock types. These thermal properties for the goaf and backfill material are often uncertain.
- **The reservoir water temperature**, which depends on the depth range of the interconnected mine workings and the geothermal gradient, defines the heat available (alongside the porosity)
- **Thermal Recharge**. The geothermal and surface heat flux (e.g. solar radiation) controls the conductive heat recharge rate in the system, while convective heat transport is controlled by groundwater inflows.
- **The heat transfer processes**. These result from the combined effect of the hydraulic and thermal settings and properties (e.g. impact of flow, natural convection, density variations and stratification)

2.1.3 System Design

- **The well location**, **depth and spacing** (for abstraction-reinjection systems). These must ensure hydraulic connection between the wells and, depending on the system's permeability and flow/pumping rate, ensure sufficient water residence time in the system (pathway length) to permit thermal recovery and prevent thermal breakthrough.
- **The pumping rate**. It refers to the achievable pumping rate (i.e. function of the reservoir properties) or the rate required to have an economically viable system (i.e. energy needs).
- **The operational set-up** (e.g. inter- or intra-seam abstraction-reinjection, abstraction with discharge, cyclical production, heat/cool storage).
- **The pumping head.** This will impact both the efficiency and economics of heat recovery.
- **The reinjection location and temperature.** These control the heat recoverable via cooling of the host rock. A cool 'sink' may aggravate with limited hydraulic recharge and deplete the system in heat.

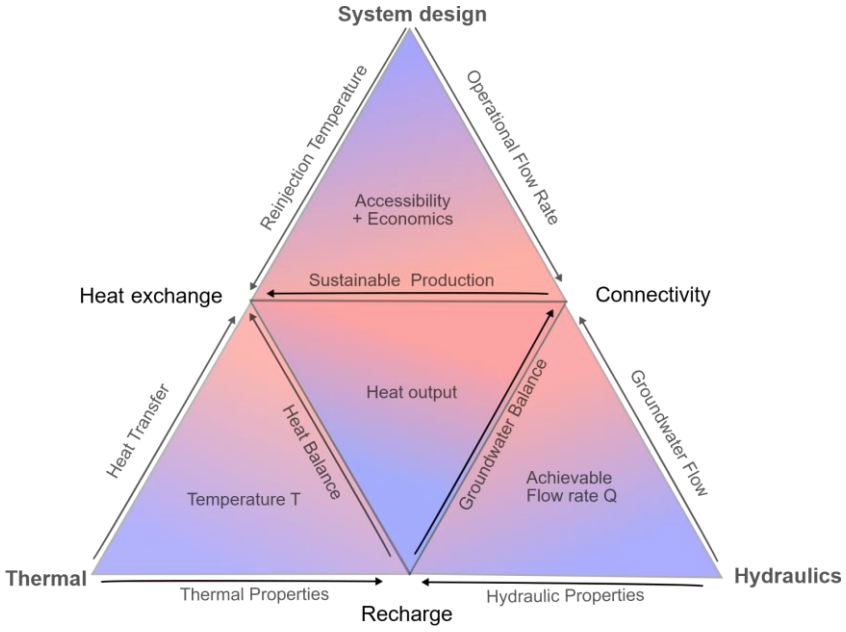


Figure 2 Interplay between factors controlling the heat recoverable from mine water geothermal systems

2.2 Theoretical Heat Resource Estimates

Heat resources are distributed in different units of a mine water system with their own hydraulic and thermal properties (Figure 3). Based on the volumetric heat in place approach, the total theoretical heat content in a mine can be summarized as:

$$E_{MTV} = E_{MWV} + E_{MRV} + E_{CFV} + E_{URV} \quad (1)$$

With E_{MTV} the total energy in the considered volume [J], which includes E_{MWV} the energy in the mine water [J], E_{MRV} the energy in the mined rock volume [J], E_{CFV} the energy in the caved and fractured volume [J], and E_{URV} the energy in the undisturbed rock mass [J]. A detail of each term is provided in the following subsections.

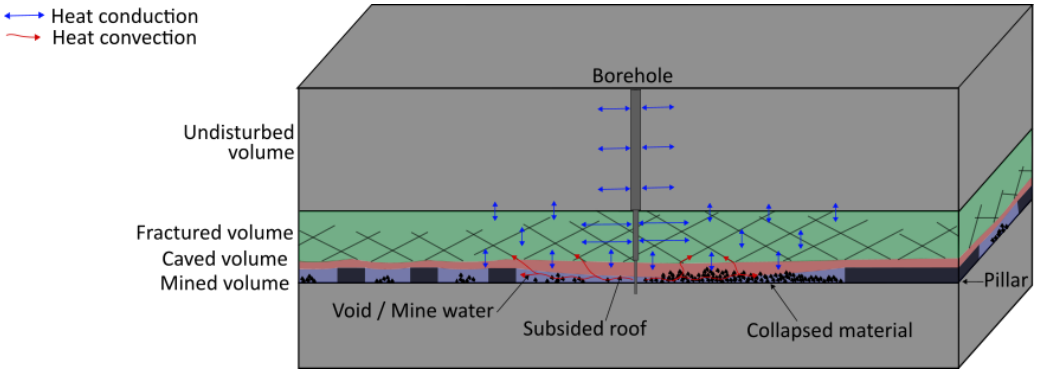


Figure 3 Conceptual model of a mine working

2.2.1 Heat in Mine Water

The heat potential in flooded coal mines is generally associated with the volume of mine water contained in mining voids (e.g. mine workings, shafts, roadways). Whilst shafts and roadways may remain open or partially open, the void volume in mine workings mainly depends on the volume of coal extracted, which is determined by the mining method (c. 80% in longwall mining and 30-70% in and pillar-and-stall; Younger and Adams., 2002, Garrard and Taylor, 1988), and on the post-mining volume changes resulting from collapse, backfilling, compaction, fracturing of the roof and subsidence (Wolkersdorfer, 2008). The residual void volume in coal mine workings can be expressed as:

$$V_{MW} = \frac{A \times h_m}{cos(\alpha)} \times c \quad (2)$$

With V_{MW} [m³] the volume of mine water filled void, A the worked area [m²], h_m the extracted thickness [m], α the coal seam inclination (Rogoz, 1978) and c a correction factor accounting for backfilling, subsidence and compaction. Jessop et al. (1995) suggested that in both longwall and pillar-and-stall mining areas, the residual void volume is in the order of 25%, whilst Malolepszy (2003) proposed that it varies between 5-40% depending on the mining method. In pillar-and-stall areas, where convergence of the roof/floor is limited, c. 50% of the mining voids were suggested to remain open (Younger et al., 2002), against 20% in longwall mining areas (Gillespie et al., 2013). A goaf porosity of 30% was considered by Younger and Adams (1999). Whitworth (2002) suggested that the residual void volume represents 10% of the extracted height in areas of total extraction, whilst Bazargan and Demollin (2008) used values of 70% and 85% to estimate the residual volume fraction in caved and backfilled zones, respectively.

The heat content in the mined volume can be calculated as (e.g. Raymond and Therrien, 2008):

$$E_{MV} = E_{MWV} + E_{MRV} = V_{MW}\rho_w c_w \Delta T_w + V_{MR}\rho_r c_r \Delta T_r \quad (3)$$

The first term, E_{MWV} [J], represents the energy contained in the water in the void space, with V_{MW} the volume of mine water filled voids [m³], $\rho_w = 1000$ kg/m³ and $c_w = 4184$ J/(kg.K) the mine water density and specific heat capacity, respectively, and $\Delta T_w = T_w - T_{ref}$ the water temperature change [K] (i.e. difference between the water temperature T_w and a reference temperature T_{ref}). The second component aims to account for the heat contained in rocks in the mining horizon, which includes unmined rock (e.g. pillars), collapsed roof material (goaf) or backfilled material, with V_{MR} the total volume of the rock in the mine workings, ρ_r the rock density [kg/m³], c_r [J/(kg.K)] the rock specific heat capacity, and $\Delta T_r = T_r - T_{ref}$ the rock temperature change (i.e. difference between the initial rock temperature T_r and a reference temperature T_{ref}). In many approaches to resource estimation, the theoretical heat contained in the water E_{MWV} (i.e. the first term in equation 3) is often the only term considered and calculated.

2.2.2 Heat in the Caved and Fractured Zones

Above the mine working, a caved zone representing 1.5 to 6 times the extracted thickness, and an overlying fractures zone c. 10 – 60 times the mining height commonly develops as a result of the roof collapse and the induced stresses (NCB, 1975; Younger and Adams, 1999; Andrews et al., 2020). The height of each zone, which mainly depends on the mining height and roof strength, can be determined by using empirical formulas (e.g. Guo et al., 2018) or available data at the site of interest (e.g. borehole logs).

Following Eq. 3, the heat content in the combined caved/fractured zone can be calculated as:

$$E_{CFV} = V_{CFZ}[\varphi_{CFZ}\rho_w c_w \Delta T_w + (1 - \varphi_{CFZ})\rho_r c_r \Delta T_r] \quad (4)$$

The first term represents the energy contained in the water in the combined porous/fractured space of volume $V_{CFZ} = A \times (h_C + h_F)$ and porosity φ_{CFZ}, where h_C and h_F are the height of the caved and fractured zones, respectively, and A the panel area. The second term accounts for the heat in rocks in the caved/fractured zone.

2.2.3 Heat in the Undisturbed Overburden Rock

The heat in the overburden rock can provide a heat reserve for the utilization of mines as a heat source over the long term via conductive heat transfers from/into the rock mass. The volume of the rock mass affected by cooling will increase over time at a rate that depends on e.g. the injection temperature, flow rate, rock thermal conductivity. The theoretical heat in this unit can be calculated following the volumetric method, as:

$$E_{URV} = V_{URV}[\varphi_{URV}\rho_w c_w \Delta T_w + (1 - \varphi_{URV})\rho_r c_r \Delta T_r] \quad (5)$$

With V_{URV} the overburden volume affected and φ_{URV} the matrix porosity.

2.3 Hydro-Thermal Methods to Heat Resource Characterization

2.3.1 Hydraulic and Thermal monitoring

Monitoring in boreholes, shafts or at discharge points may provide in-situ observations of the temperature and water level changes at different locations of an interconnected system. These can be used to characterize the hydraulic and thermal recharge boundaries and support the development of a conceptual model.

Thermal profiling in shafts and/or boreholes record the variations in temperature with depth, allowing characterization of the geothermal gradient and/or identify physical and chemical water changes. Stratification of salinity and temperature is a common phenomenon in flooded mines related to free convection processes, that can inform on the depth of interconnected levels and the water quality (Mugova et al., 2025).

2.3.2 Flow tests

Pumping tests can, via the monitoring of pressure change in response to different flow rates, provide insights into the extent of the hydraulic connections within the system and the transmissivity. They allow determining what flow can be achieved for production or reinjection without significant pressure drop or build up.

Flow discharge from flooded mines can be both gravity driven or with the aid of pumps (usually to maintain a desired groundwater level). Time-series of flow rate and temperature measurements can be used to estimate the groundwater recharge rate and get insights into the temperature variations of the resource (Farr et al., 2016).

Tracer tests have been successfully conducted in underground flooded mines (Wolkersdorfer, 2008) to evaluate the hydraulic characteristics, the flow paths, residence time of water and potential connectivity between an injection and abstraction point.

2.3.3 Thermal Tests

Thermal response tests, combined with numerical modelling, are useful to characterize the rate of heat transfers in the rock mass around a borehole and refine the determination of rock properties (e.g. thermal conductivity). This is of particular importance for storage applications. Observations can be used to identify the volume of affected rock and delineate the extent of the resource available for heat recovery/storage.

Thermal tracer tests, which involve the injection of water at a different temperature than the mine water in the reservoir (open loop), can inform on the conductive and convective heat exchanges, thermal dispersion effects, on potential short-circuiting between an injection and abstraction well, and provide data to support numerical modelling (Kocabas, 2005). Heat injection or heat extraction experiments were used at the UK Geoenergy Observatory in Glasgow, providing key insights into the system interconnectivity and the potential of the mine for geothermal utilization and heat storage (e.g. Receveur et al., 2026; Gonzalez Quiros et al., 2025b).

2.4 Energy Recovery Estimates

The thermal heat energy recovered at the surface via the pumped or discharging mine water (e.g. Bailey et al., 2016; Farr et al., 2016) is expressed by:

$$H_{REC}\ (W) = Q\rho c_w \Delta T_w \quad (6)$$

With Q the pumping/discharge rate [m^3/s], ρc_w the volumetric heat capacity of the mine water [$J/(K.m^3)$], ΔT_w the temperature change at the heat exchanger [K].

By integrating this value over a given operational duration t[s], the total energy extracted can be calculated as

$$E_{REC}\ (J) = Q\rho c_w \Delta T_w\ t \tag{7}$$

A challenge in geothermal energy is to assess or predict what fraction of the calculated theoretical heat in place can be recovered at the surface during the operational phase of the project. In 'conventional' geothermal resource assessment, a recovery factor can be calculated by:

$$R = \frac{E_{REC}}{E_{MTV}} \tag{8}$$

This represents the ratio of the thermal energy recovered at wellhead (E_{REC}, Eq. 7) to the thermal energy initially present in the system (E_{MTV}, Eq. 1) is generally introduced, and often chosen arbitrarily, to account for the uncertain parameters and reservoir properties that will impact the energy recoverable (Ciriaco et al., 2020). However, this approach has larger limitations for mine water heat resource assessment due to the inherent complexity of these systems and heterogeneous spatial distribution of voids and properties.

3 RESULTS AND DISCUSSION

This section applies the methods described above to real sites in the United Kingdom. We present real data from a variety of systems and discuss what is the relevance for geothermal exploitation. Data from short or long-term flow/pumping tests or from heat injection-abstraction experiments are used to illustrate endmembers and understand the concept of sustainability of heat utilization for mine-water systems.

3.1 UKGEOS Glasgow Observatory

3.1.1 Introduction to the site

The UK Geoenergy Observatory (UKGEOS) in Glasgow, Scotland, is an at-scale research facility accessing the flooded mine workings of the Farme colliery, providing a unique opportunity to study mine-water geothermal and mine thermal energy storage (Monaghan et al. 2022). Five mine-water boreholes are drilled into two mine workings, the Glasgow Upper (GU) at 50 m depth and the Glasgow Main (GMA) at 90 m depth. The boreholes are equipped with a submersible pump and injection mains and connected to a heat centre with heat pump/chiller, allowing multiple combinations of heat injection-abstraction experiments at rates of 3-12 l/s.

3.1.2 Theoretical heat in place

The theoretical heat in place in the reservoir associated with the GU mine working was calculated according to the method presented in Section 2.1, assuming ρ_r = 2500 kg/m^3 and c_r = 930 J/(kg.K). At the Glasgow Observatory, the GU seam is on average h_m= 1.26 m thick and extends horizontally ($\alpha = 0$) over an area A ≈ 4.67 km^2 (Gonzalez Quiros et al., 2024). Using $\Delta T_w = \Delta T_r = 5$°C for the comparative purposes of this study, the theoretical heat potential contained in the water filled voids (Eq. 3) of volume V_{MW} = 1.8 hm^3 (assuming c = 0.3), is E_{MWV} = 37 TJ (10.3 GWh). Considering a rock volume V_{MR} = 4.1 hm^3 with a heat content of E_{MRV} = 45 TJ (13.3 GWh), the total heat in the mined volume is E_{MV} = 85 TJ (23.6 GWh).

Information from another borehole accessing the GU at the Observatory indicated a zone with open fractures extending *c*. 6 m (h_{CFZ}) above a pillar-and-stall area (Monaghan et al. 2021). This allowed, for this case study, to estimate a theoretical heat capacity for the caved-fractured zone E_{CFV} = 378 TJ (105 GWh), with V_{CFZ} = 28 hm^3 and φ_{CFZ} = 0.2 (Eq. 4). The average height to an overlying thermal seal mudstone layer recorded in the Observatory boreholes was also used to estimate the overburden thickness h_{URV} = 5 m and derive the theoretical overburden heat capacity E_{URV} = 293 TJ (81.4 GWh), with V_{URV} = 23.4 hm^3 and φ_{URV} = 0.1 (Eq. 5). This results in a high level, low confidence total thermal capacity of E_{MTV} = 756 TJ (210 GWh) for the reservoir associated with the GU mine workings.

3.1.3 Thermal Tracer Tests

A 25-day heat extraction experiment was conducted at the Observatory in 2023. The water was abstracted from the GU mine workings at a rate of 6 l/s and a temperature of c. 11.95°C and reinjected into the same mine workings at 135 m distance. Indication of thermal breakthrough in the abstraction boreholes was observed after 11 days (Gonzalez Quiros et al., 2025b). Another two tests, one with the same configuration (135 m distance) in the GU mine working but at a rate of 12 l/s resulted in thermal breakthrough after less than 4.8 days, while a test in the GMA (119 m doublet separation) resulted in thermal breakthrough after 2.3 days (Gonzalez Quiros et al., 2025a), indicating higher transmissivity and better connectivity in the GMA than in the GU. Experiments with abstraction from one mine working (GU) and reinjection in the other (e.g. GMA) have not shown any signs of thermal breakthrough, supporting the interpretation of limited hydraulic connectivity between both mine workings (Gonzalez Quiros et al., 2024).

3.1.4 Implications for Geothermal Exploitation

Estimates of the theoretical heat recoverable from the GU and GMA (Eq. 7) using information from these three experiments reported previously can be provided assuming a $\Delta T_w = 5°C$. For the GU it results in a E_{REC} = 119 GJ (for the first test at 6 l/s and thermal breakthroughs after 11 days) and a E_{REC} = 104 GJ for the second test (12 l/s and 4.8 days thermal breakthrough). For the GMA test it results on a E_{REC} = 50 GJ (12 l/s and 2.3 days thermal breakthrough). These values represent less than 1% of the calculated thermal capacity of the mine (E_{MV}). However, the in-seam configuration of these tests shows that the connectivity between the injection and abstraction boreholes plays a key role and would lead to non-sustainability of the system if it was to be operated for geothermal exploitation, which is not the case as the site is used for geothermal experimentation. When in inter-seam operation (e.g. abstraction from GU and reinjection to GMA) the calculated annual energy extraction at the maximum operational flow rate (12 l/s) assuming $\Delta T_w = 5°C$ would result in a value of E_{REC} = 8 TJ (2 GWh).

3.2 East Fife Coal Mines

3.2.1 Introduction to the site and long-term flow test

Mine water levels have been recovering in the East Fife coalfield in Scotland since operational pumping ceased in 1995 (Whitworth, 2002). Continuous preventative pumping by The Coal Authority (now known as the Mining Remediation Authority) from the Frances colliery began in 2004 to maintain the mine water at an agreed level and prevent an uncontrolled break out. A long-term pumping test began at the nearby Michael colliery in 2016 to support the pumping requirements at Frances (Figure 4). There is a large variety of pumped and gravity discharge data available in the East Fife coalfield, with some discharge being monitored continuously and others having a single point reading.

3.2.2 Heat in Place Estimations

A high-level estimate of the heat in place for the East Fife coalfield was undertaken using GIS data from the Mining Remediation Authority. The volume of each coal seam was calculated using the seam area and average thickness for panels between 50 and 300 m deep. 91% of the seams in this area were mined using total extraction so a 50% correction factor was applied to the mined volume to account for potential collapse of the mine workings. Using the first term in Eq. 3, the heat available for this volume of water considering ΔT_w = 5°C gives E_{MWV} = 3.5 x10^3 TJ (972 GWh). This doesn't consider the fractured zone above or below the seams due to limited data.

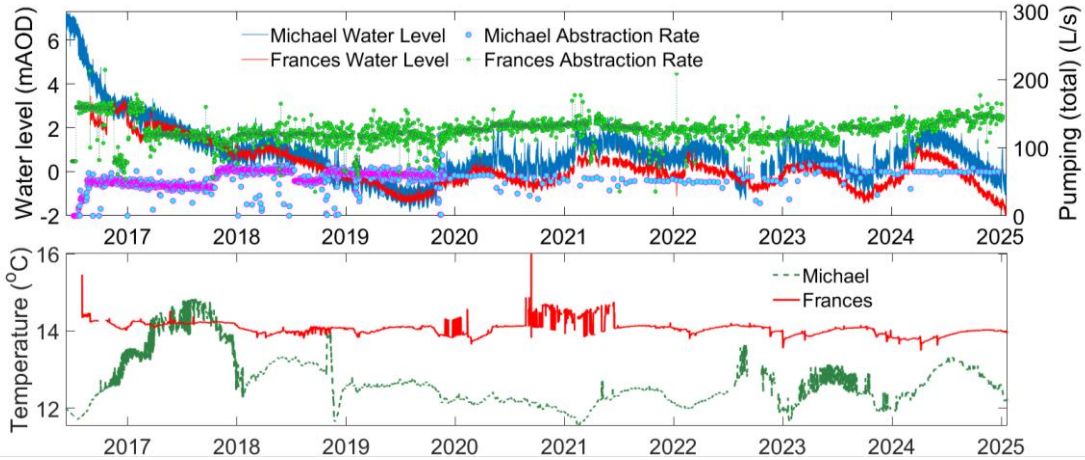


Figure 4 a) Water level variations and b) temperatures between 2016 and 2025 in Michael and Frances.
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3.2.3 Hydraulic and Thermal Monitoring

Abstraction rates at Frances and Michael averaged 120 l/s and 60 l/s between 2016 and 2025, respectively (Figure 4a). Following the onset of abstraction at Michael in 2016, water levels (WL) declined from c. 6 mAOD to 3 mAOD within a few months. Between 2017 and 2020, a similar decline in WL down to -1 mAOD was observed at both sites, suggesting the strong system interconnectivity. From 2020, the WL depicted similar yearly fluctuations around an average of 0.5 mAOD at Frances and 1 mAOD in Michael until mid-2024, suggesting an equilibrium between the abstraction and natural hydraulic recharge, and the potential for sustained flow rate. From mid-2024, a slight increase in the pumping rate in Frances resulted in a larger drawdown in the mine area.

Temperature variations at Michael and Frances depicted yearly fluctuations with an average of 12.5°C and 14°C between 2016 and 2025, respectively, with no sign of thermal drawdown (Figure 4b). The stable average temperature throughout this extensive (6 years) pumping period suggests sufficient heat recharge in the system favored by the large system size and sufficient transmissivity.

3.2.4 Implications for Geothermal Exploitation

Long-term flow test results showing sustained flow rate, water level and temperature provide a reliable source of information to determine the heat recoverable from a system. Using Eq. 7 with a total abstraction rate of 180 l/s and assuming $\Delta T_w = 5°C$ (noting that no cooled water is reinjected), the theoretical annual heat recoverable from the two main discharges in East Fife, the Frances and Michael treatment schemes, is E_{REC} = 120 TJ (33 GWh). This is c. 30 times smaller than the heat in place calculated for the volume of water in the coalfield, but in line with the sustainable annual heat available of 200 TJ estimated using the method in Todd et al. (2019).

3.3 Cronton

3.3.1 Description of the Site and Pumping Test

The Cronton Colliery, located between Liverpool and Warrington in the Lancashire Coalfield, was estimated to reach complete recovery between 2020 and 2021 but updated projections based on monitoring suggested that the mine water level would decant into an adjacent aquifer by 2025. A short-term pumping test was undertaken by the Mining Remediation Authority in 2024 to evaluate the behavior of the system and determine the risk from mine water to the adjacent aquifer. The step test with abstraction rates of 2, 4 and 6 l/s indicated a rapid and linear decline in water level from 6 to -8 mAOD in 2 months (Figure 5). The onset of pumping was associated with a sudden temperature increase from 11 to 16°C, with the temperature remaining stable during the length of the experiment. As pumping stopped, water started to slowly recover but remained 3 m below the pre-test levels after 6 months and would take c. 1 year to return to pre-pumping levels. The results from this test indicated that the risk to the aquifer was negligible due to the flow rates and geochemistry encountered.

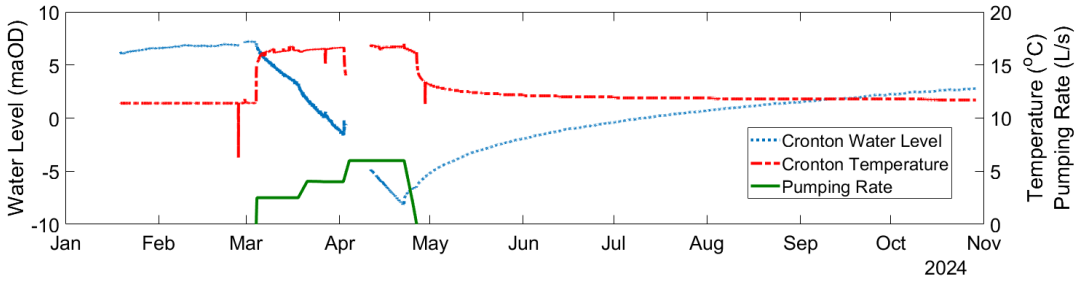


Figure 5 Water level, temperature change and pumping rate during a 10-month flow test at Cronton, UK.
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3.3.2 Implications for Geothermal Exploitation

Assuming $\Delta T_w = 5°C$, the annual energy output in that system with maximum flow rate of 6 l/s would be E_{Rec} = 4 TJ (1 GWh). However, the response of the system to pumping shows unacceptable pressure drawdown with no sign of stabilization, even with very low flow rate and thermal output, suggesting that either the lack of natural hydraulic recharge of the system or not appropriate hydraulic properties facilitating groundwater flow, or a combination of both, would make the system unsustainable for geothermal utilization.

3.4 Sustainability in Mine Water Geothermal Energy

Our analysis has tested methods to determine mine water geothermal system heat estimation and sustainability using end member examples. Historical discharge data from Fife shows that natural hydraulic recharge balances the volume pumped for long term water level management and would be sustainable for 33 GWh local energy needs. Pumping test data from other potential sites, such as Cronton, Lancashire indicates that such tests play a critical role in characterizing achievable flow rates and establishing system sustainability. If reinjection is needed, the interplay between the system hydraulic properties and system design plays a key role in system sustainability (Figure 6), as illustrated by datasets from the UK Geoenergy Observatory in Glasgow.

Theoretical heat static or volumetric estimates applied in mines are complex as a result of the high heterogeneity and specificities of each mine. The distribution and properties of the void space (including mined, caved and fractured zones) result from a combination of the mining methods, the history and geometry of the mine (e.g. interconnectivity between shafts, roadways, goaf, fractures) and the rock properties of the surrounding rock. In

addition, and in contrast to conventional aquifers, these form different mining units with a broader range of highly variable and uncertain properties. Static methods, although they are useful to assess the heat in place, are therefore limited by the knowledge of the rock volume and heat accessible in the long term.

The main factors for heat accessible and dynamics of heat recovery are the type of system (e.g. reinjection or discharge), the interplay between the reservoir characteristics (e.g. mine interconnectivity, volume of fractured rock), the system's design and its operational parameters (e.g. flow rate), and groundwater recharge. Flow tests are a key tool to collect representative data, allowing insights into the transmissivity of the system, its productivity and injectivity (for systems with reinjection). These are essential in the early stage of the development of a geothermal infrastructure to determine the achievable flow rates, production temperatures and heat output. In addition, long-term monitoring can provide information on the system's behavior on a large scale and overcome uncertainties in mine geometry away from a borehole.

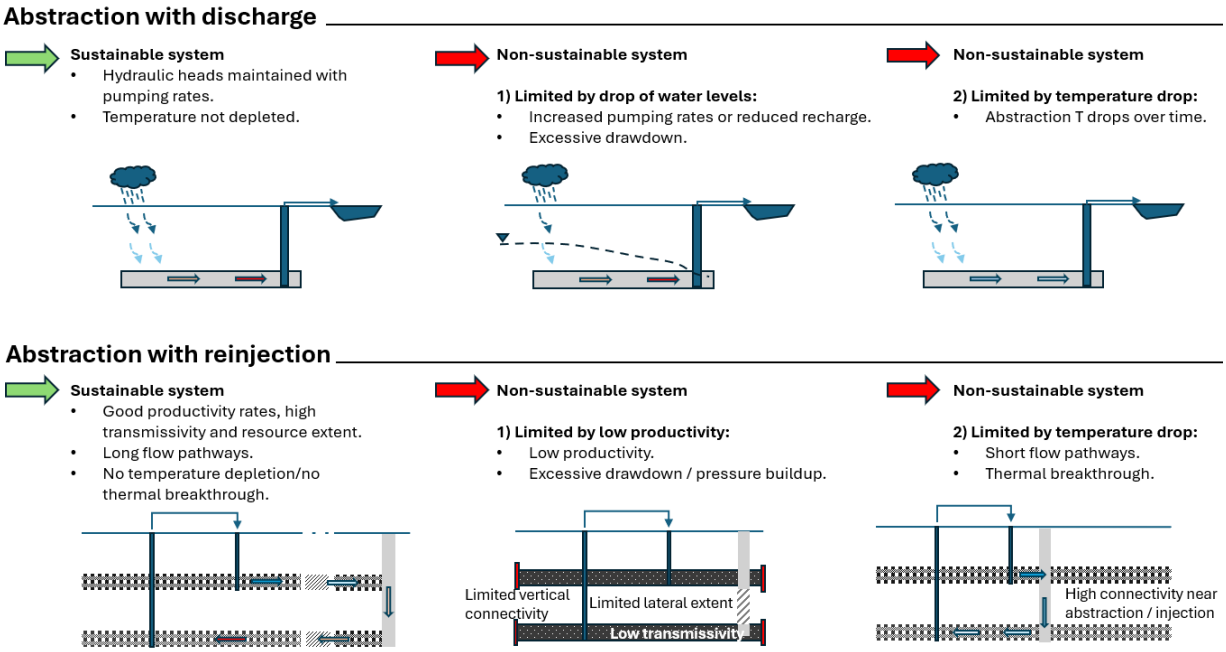


Figure 6 Summary of the sustainable heat recovery factors for a system with discharge or reinjection

4 CONCLUSION

Working towards best practice for planning sustainable heat recovery mine water geothermal systems, we have used three end member examples to show that optimizing the design of a mine water heat abstraction-reinjection system, which involves finding the best set up to promote access to heat and prevent thermal breakthrough, has a key impact on the long-term heat recovery potential. Where conventional heat-in-place and recovery factor methods are less relevant for mine water geothermal resource assessment, optimized heat recovery can be achieved based on the knowledge of the geometry of the system, through initial pumping tests and long-term monitoring. These must be used to find the balance between the achievable flow rates, that depend on the volume of accessible water and the reservoir transmissivity, and the energy needs. Preventive or corrective measures could also be implemented to guarantee heat recovery in the system in the long term, including heat/cool storage, cyclical production, and should be considered in the initial stages of development.

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